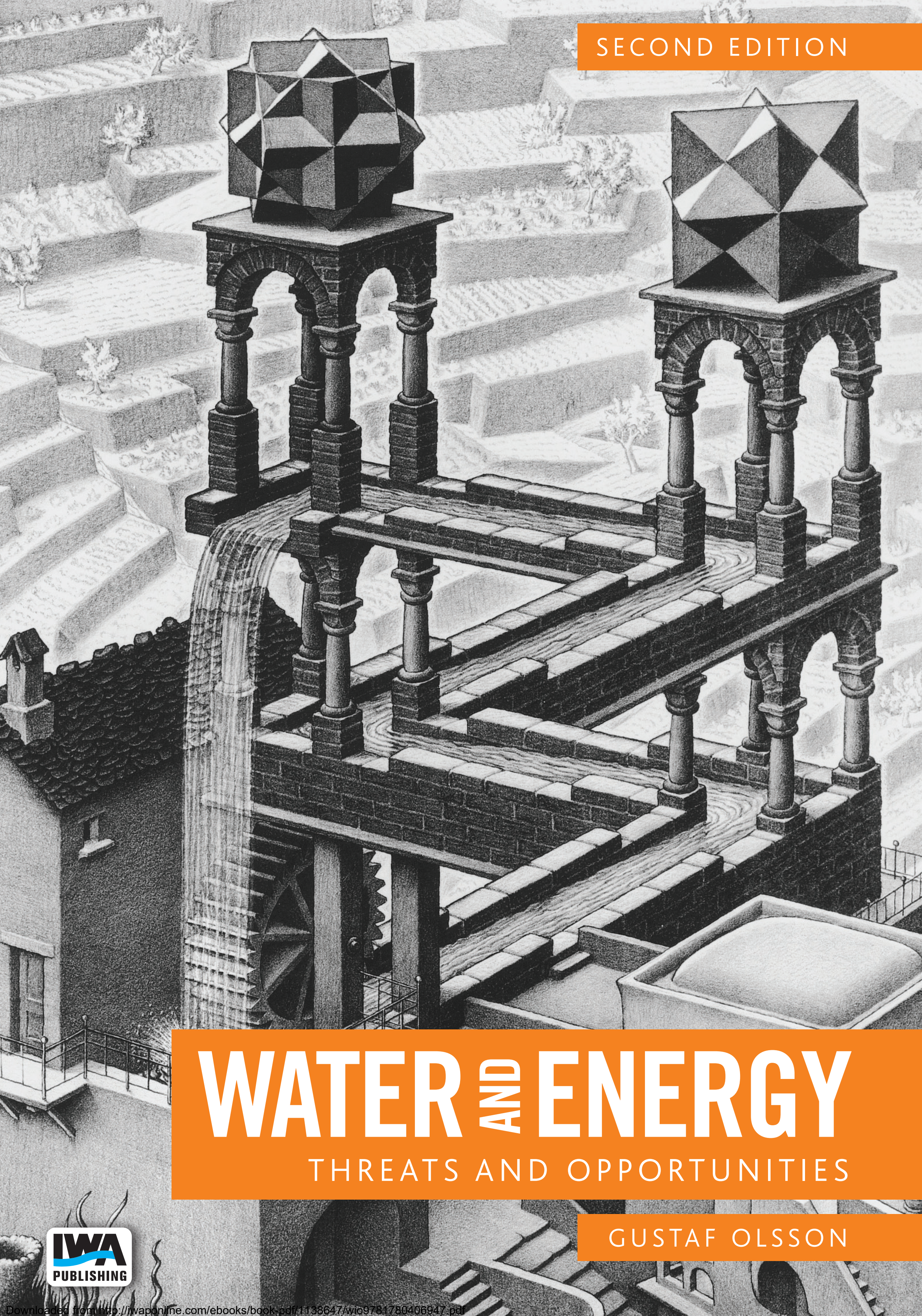

SECOND EDITION

WATER AND ENERGY

THREATS AND OPPORTUNITIES

GUSTAF OLSSON

IWA PUBLISHING

Water and Energy

'Water and Energy – Threats and Opportunities by Emeritus Professor Gustaf Olsson, is a milestone book in the efficient use of two important resources: water and energy. It is remarkable that due to increasing specialization among professionals in the different fields, water and energy are not optimized jointly. The production of energy requires water, while the supply of water services demands energy. Water and energy are the drivers for almost all economic activities, and are of such importance that they are at the origin of conflicts throughout the world.'

Blanca Jiminez Cisneros, Director of the Division of Water Sciences, UNESCO, Paris

'This book comes at the right time. Conflicts about hydropower projects …New perspective on waste water as an energy source … growing dependence from seawater desalination for cities in arid areas … these are warning signals that water and energy security are increasingly linked. Gustaf Olsson's work is a *precious* reference, encompassing the complexity of the subject and providing a wealth of data. Because he has shared his career between energy and water management, Gustaf Olsson has a balanced and wide ranging perspective.'

Jacques Labre, Co-ordinator of Thematic Priority Harmonize energy and water,
at the 6th World Water Forum (Marseilles, March 2012)

'In producing his latest book, Water and Energy, Professor Olsson has put together an extremely valuable compendium of vital information and insights into the highly crucial relationship between two essential in modern life water and energy. In so doing, Professor Olsson is providing the largely separate communities of both water professionals and energy professional with a foundation for jointly understanding, simplifying and in many cases demystifying the myriad of water and energy interfaces. When one considers the significant carbon footprint of water production, use and treatment and the even more significant water footprint of energy production and use, the contribution of Professor Olsson's book will be greatly appreciated in helping to illuminate the pathway ahead a pathway that will lead us to conquer the essential challenge of making the use of water and energy both and jointly, an order of magnitude more efficient than today.'

Paul D. Reiter, Former Executive Director, International Water Association

'In authoring the book "Water and Energy Threats and Opportunities" Professor Gustaf Olsson provided a comprehensive and equally impressive guide in to the critical and many times complex relationship of energy and water. The book provided detailed insights to all parts of what is normally referred to as the "water and energy nexus"; such as different drivers for water and energy, different impacts on water resources from types of energy generation, technology options as well as suggesting steps to be taken in order to better address emerging challenges. The dynamic relationship between water and energy is under constant change and evolvement as demand for different fuel types emerges, new technologies are employed and science makes breakthroughs. This second edition of the book captures many of these changes offering even more depth and width to the reader as professor Olsson once again delivers a key product enabling better understanding of the water and energy nexus.'

Andreas LINDSTRÖM, Unit leader, Water-Energy-Food,
Stockholm International Water Institute

Water and Energy

Threats and Opportunities

Second Edition

Gustaf Olsson

IWA PUBLISHING

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Acronyms

AD	anaerobic digestion
ADB	Asian Development Bank
ARD	acid rock drainage
AMD	acid mine drainage
ASCE	American Society of Civil Engineers
AQUASTAT	FAO's information system on Water and Agriculture, www.fao.org/nr/water/aquastat
BMP	biochemical methane potential
BOD	biochemical oxygen demand, a measure of the organic carbon content in the wastewater
BWR	boiling water (nuclear) reactor
BWRO	brackish water reverse osmosis
CEHRD	Center for Environment, Human Rights and Development (Nigeria)
CCGT	Combined-cycle gas turbine
CCS	carbon capture and storage
CHP	combined heat and power
CNG	compressed natural gas
COD	chemical oxygen demand
COP	Conference of the Parties (UNFCCC)
CSP	Concentrating solar power
DMA	district metered area
DOE	Department of Energy (USA), www.doe.gov
EIA	environmental impact assessment
EMS	energy management system
EOR	enhanced oil recovery
EPA	see USEPA
EPRI	Electric Power Research Institute (USA), www.epri.com
EU	European Union
FAO	The Food and Agriculture Organization of the United Nations, www.fao.org
FO	forward osmosis
GEO	Global Environmental Outlook
GGFR	Global Gas Flaring Reduction Partnership
GISS	NASA Goddard Institute for Space Studies, www.giss.nasa.gov
GHG	greenhouse gas
GNP	gross national product
GWP	global warming potential
GWRC	Global Water Research Coalition

HFC	hydrofluorocarbons
HVAC	Heating, ventilation and air conditioning
IAC	Inter Academy Council, www.interacademycouncil.net
ICA	International Court of Arbitration, www.iccwbo.org/court
ICA	Instrumentation, Control and Automation
ICOLD	International Commission on Large Dams, www.icold-cigb.net
IGCC	Integrated gasification combined-cycle
IEA	International Energy Agency, www.iea.org
IFPRI	International Food Policy Research Institute, www.ifpri.org
IHA	International Hydropower Association, www.hydropower.org
IIASA	Int. Institute for Applied Systems Analysis, www.iiasa.ac.at
INSHP	International Networking on Small Hydropower, www.inshp.org
IPCC	Intergovernmental Panel on Climate Change, www.ipcc.ch
ISO	International Standards Organization, www.iso.org
IUCN	The World Conservation Union, www.iucn.org
IWA	International Water Association, www.iwahq.org
IWRM	integrated water resources management
LNG	liquid natural gas
MDC	microbial desalination cell
MDGs	Millennium Development Goals
MED	Multiple Effect Distillation
MF	microfiltration
MFC	microbial fuel cell
MMS	Minerals Management Service, in 2011 replaced by the Bureau of Ocean Energy Management (BOEM) www.boem.gov, and the Bureau of Safety and Environmental Enforcement (BSEE), www.bsee.gov
MSF	Multistage flash distillation
NASA	The U.S. National Aeronautics and Space Administration, www.nasa.gov
NF	nanofiltration
NOAA	National Oceanic and Atmospheric Administration, www.noaa.gov
NOSDRA	National Oil Spill Detection and Response Agency (Nigeria)
NRW	non-revenue water
NSIDC	National Snow and Ice Data Center, nsidc.org
OECD	Organization for Economic Cooperation and Development, www.oecd.org
PFC	perfluorocarbon
POME	palm oil mill effluent
ppm	parts per million
PRO	pressure retarded osmosis
PV	(Solar) photovoltaic
PWR	pressurized water (nuclear) reactor
RE	renewable energy
RO	reverse osmosis
SCADA	supervisory control and data acquisition
SDWA	Federal Safe Drinking Water Act
SHP	small hydropower
SIDA	Swedish International Development Cooperation Agency, www.sida.se
SIWI	Stockholm International Water Institute, www.siwi.org

SPDC	Shell Petroleum Development Company of Nigeria Limited, www.shell.com.ng
SWRO	sea water reverse osmosis
TS	total solids
TWM	transboundary water management
VFA	volatile fatty acids
VOC	volatile organic carbon
UF	ultrafiltration
UNDESA	United Nations Department of Economic and Social Affairs, www.un.org/en/development/desa
UNDP	United Nations Development Programme, www.undp.org
UNEP	United Nations Environment Programme, www.unep.org
UNESCO	United Nations Educational, Scientific and Cultural Organization, www.unesco.org
UNFCCC	United Nations Framework Convention on Climate Change, http://unfccc.int
UNPD	United Nations Population Division, www.un.org/esa/population/
USEPA	U.S. Environmental Protection Agency, www.epa.gov
VC	Vapour compression
WBCSD	World Business Council for Sustainable Development, www.wbcsd.org
WCD	World Commission on Dams, www.internationalrivers.org
WEC	World Energy Council, www.worldenergy.org
WEF	World Economic Forum, www.weforum.org
WFD	The EU Water Framework Directive, ec.europa.eu/environment/water/water-framework
WHO	World Health Organization, www.who.int
WMO	World Meteorological Organization, www.wmo.int
WSI	water stress index
WSSTP	Water Supply and Sanitation Technology Platform, www.wsstp.eu
WWAP	UN World Water Assessment Programme
WWC	World Water Council, www.worldwatercouncil.org

A guide for the reader

The main purpose of the book is to create an awareness of the important couplings between water and energy. It is an attempt to show how energy is used – and misused – in all the various water cycle operations as well as to demonstrate how water is used – and misused – in energy production and generation. The book does not aim to show 'how to design' or to solve some of the intricate conflicts. Instead it tries to systematically list ideas, possibilities and some results. Of course there are many solutions and the hope is that the book can be the entry point to technical and scientific literature on the various topics.

Parts One and Two describe the **water-energy nexus**, the conflicts and competitions and the couplings between water security, energy security, food security and their relations to the climate change and the world population increase.

Part Three is about **water for energy**. The aim of this part is to show how much energy production and conversion depend on water availability and how these operations influence both available water quantity and quality. As a consequence all energy system planning, design and operation have to take both water and energy into consideration.

Part Four is about **energy for water** and demonstrates how water production and treatment depend on energy. However, wastewater operations can also generate energy. The aim of this part is to show that a lot can be done to adjust equipment, develop processes and apply advanced monitoring and control to save energy for the water operations and to recover energy content of wastewater.

In part Five we try to translate ideas into **action plans**. Hopefully this can inspire to actions that we have not yet anticipated. The water-energy issue is not only about technology. Our attitudes and our lifestyle can significantly influence the consumption of both water and energy. We all have to be reminded that water is energy and energy is water.

The bibliography is certainly not complete but is hopefully a good entry to the more specialized literature. A glossary is provided.

In Appendix 1 the conversion of units is described, which is necessary in order to compare all kinds of statistics material. All physical and chemical quantities are expressed in metric units. Appendix 2 depicts the energy content of some common fuels.

The book is aimed for various kinds of readers, for example:

- The *politician* and *decision maker*, to hopefully get some holistic view; investors are among the important decision makers;
- The *interested engineer* who wishes to find out about the key issues and to understand the strong driving forces from the increasing population, climate change and the food supply in the world;
- The *student* who looks for an overview of future challenges and new possibilities;
- The *planner* – water and energy have to be planned together;
- The *water professional* – it is not only a matter of operating water systems efficiently;

- The *designer* of water and wastewater systems – how energy comes into the picture;
- The *operator* and *manager* of water and wastewater operations;
- The *power and energy professional* – mostly the water issue is forgotten – until there is a water scarcity;
- The *researcher* – looking for connections between different specialties and why cross-disciplinary research is needed.

In fact, we have to form **strategic alliances** between investors, city planners, architects, regulators, farmers, manufacturers, process engineers and researchers. In other words: the future requires of us to think more holistically about water, energy and food.

G.O.

Preface

This book considers two of the three crucial ingredients for our survival. No doubt that oxygen is the most important. The brain can stay alive for 4 to 6 minutes without oxygen. After that cells begin to die. The second most important component is water. When faced with a critical situation, clean drinkable water is often the most important consideration. People have survived without food for weeks or even months, but go without water for even just one day and the survivor will be in desperate condition. Then comes energy. Our body needs energy for survival and we need energy to produce our food and keep us at a comfortable temperature. Still, mankind survived thousands of years without oil. The needs for a decent life can be discussed and prioritized differently.

On 28 July, 2010 the United Nations General Assembly decided that *clean water supply and sanitation is a human right*. A Bolivian-penned draft resolution says internationally endorsed water rights would 'entitle everyone to available, safe, acceptable, accessible and affordable water and sanitation.' It declares that countries unable to deliver water to their populations – despite their best efforts – should be helped through 'international co-operation and assistance.' The 1.1 billion people without access to clean, safe water still have to drink – every day. They will use about 5 liters/day/person. Most of us in water rich countries would probably not even wash the dishes in this water. Just one flush of our toilets uses more drinking water.

For my country Sweden the total electricity consumption (in 2011) corresponds to 14,800 kWh per capita and year while for the USA the amount is 12,500 kWh. The corresponding numbers are for Ethiopia 35 kWh, for Chad 9 kWh, for China 2,600 kWh and for India 480 kWh. This disturbing difference between the 'haves' and 'have-nots' has influenced my thinking.

In the following paragraphs I illustrate why I have written this book. I started my career in the 1960s as a nuclear engineer in Sweden. The energy issue was highly interesting and in that time period nuclear power generation was seen as the hope for the world. The U.S. President Dwight D. Eisenhower had delivered the famous speech 'Atoms for Peace' to the UN General Assembly in 1953. The UN organized the 'Second UN Int. Conference on the Peaceful Uses of Atomic Energy' in Geneva in 1958, often referred to as the 'Atoms for Peace conference'. This had a lot of influence on young people. Having worked with nuclear reactor stability for a couple of years my interests were increasingly directed towards automatic control. With this training I was challenged by wastewater treatment operations, in 1973. Controlling the activated sludge process was a primary target for our attempts, and our first full scale computer control of an activated sludge system was in operation in 1976. By controlling the dissolved oxygen concentration a significant amount of energy could be saved, while the microorganisms were kept in better shape. Since then I have worked in the parallel worlds of water and energy systems: to control activated sludge systems, to apply automation in water supply systems and to control electrical power systems. The research at my academic department Industrial Electrical Engineering and Automation at Lund University has dealt with automation in water systems, process industries and in electrical power systems. Still, it is only during the last few years that I have become fully aware of the high degree of interrelationships between water and energy.

Some ten years ago my wife and I visited Morocco for a short holiday during the winter season. Instead of staying on the beach we wanted to discover more of the interesting country. We had heard about the Blue People, coming from the Sahel region, so we went to Guelmim (Gulimin), found a local guide at the street and continued to an oasis at the edge of the Sahara desert. The Blue People had arrived on camels from far away and stayed in the oasis to trade goods they needed. A little pond in the oasis, around ten meters across, provided the difference between life and death. We were invited into the tent of a proud representative of the people. This was one of the great memorable moments in life. We had tea together and talked via our interpreter for hours. One of the first questions from our host was: ‘do you have water at home?’ ‘Yes’, we replied. ‘Do you have sufficient water for your cattle?’ he continued. Thinking about the wealth of water in Sweden and our clean beautiful lake close to our little summer cottage I did not know how to answer the question properly, but said: ‘yes, the cattle have enough of water’. I did not dare to mention that our lake has drinkable water. The immediate reply was: ‘why then did you come here?’ The question has followed me since then: how would you properly answer his question and not feel guilty? Having clean water available is a sign of extravagant wealth. Too often we take it for granted.

Our summer cottage is a hideaway in the forest in the south-west part of Sweden with only one neighbour within the first km. The lake is within walking distance. We have a water well and an outhouse and the luxury of electrical power. Staying in the cottage gives another perspective on water, energy and environment. While it is too easy to believe that the water supply is infinite in the city we have to save water in the cottage. We chop the wood to heat up the cottage in cold weather, and I manually take care of the outhouse waste. It is an interesting contrast to the application of automation in water and wastewater systems.

In 1975 we stayed for a sabbatical year in Houston, Texas. Despite the world oil crisis in 1973 energy was still cheap in Texas. Air conditioning was truly necessary in the summer heat with 37°C and 100% humidity. During a weekend trip we went to a pizza place to eat. We experienced the temperature shock to enter the cool restaurant. The illumination was dim and after a while I discovered a fireplace with a real fire burning! The idea was of course to make it a little more cosy. The combination of air conditioning and fire became my personal symbol of energy waste. Very few people around me appreciated my excitement about the waste of energy: ‘In Texas we grow the oil!’ Also today – 36 years later – you find people that will cool down the indoor temperature to motivate the use of the fireplace!

I have done a lot of writing in our little summer cottage. It is located in a county called Halland that used to be Danish until the peace agreement in 1645. Only a few hundred meters from the cottage there is a little creek in a deep canyon that formed the boundary between Denmark and Sweden in the 17th century. It takes four or five steps to cross the creek but it has been an important source of energy for a number of small saw mills, owned by local farmers, each one having a small piece of forest land. The creek is a micro-cosmos illustration of many great river conflicts in the world. Along the rapids of about one km stretch of the creek there used to be eight saw mills, all of them sharing the same run-of-creek water for energy. The most upstream mill controlled the gate. There were a lot of tensions how and when to use the water and it often happened that somebody opened the gate without informing the other mill owners. The last sawmill was in operation as late as in the 1930s. Several examples of conflicts of water and energy resources in the world are described in the book. It is always the same kind of competition for resources. Who owns the water? Can the upstream user handle the water independently of the downstream users? Should we accept the principle of 'using it or losing it', whether we are talking about our little creek, the Nile, the Colorado River or the Danube? More than 250 river basins around the world cross international borders, making water insecurity a cause for aggression.

I have always been fascinated by large hydro dams and in a sense I can understand that so many politicians and decision makers have been seduced by them. The picture is that the giant dam can deliver water and power to the nation. In 1971 I saw the Hoover Dam in Nevada for the first time. I looked at it with my power engineering eyes and was fascinated by the technological wonder. Comparing my old dia slides of a full Lake Mead with the alarmingly low water level of today demonstrates that the price for building many dams has been high.

The message of the book can probably be summarized in the Figure 3.1, trying to capture the dependencies between water, energy, and food securities. Being aware of the close interdependencies between water, energy and food, how should we define a solidary action plan?

This book does not attempt to deliver specific design solutions, control methods or operational guides. A main goal is to create an understanding and awareness of the close couplings and to demonstrate that the water and energy problems cannot be solved in isolation. An integrated approach to solve the complex water and energy challenges is necessary. This includes not only innovative technical solutions but several non-technical issues. Political, organizational and economic topics are equally important to address. Water utilities and power companies have to communicate in planning, design and operation. Changes in our attitudes and lifestyles are crucial if we wish to create a more sustainable use of both water and energy. Saving one MW ('Negawatt') is cheaper than producing one. There is a sense of urgency when we see the dwindling water resources in many places and when the increasing use of energy will further influence the climate change.

People have asked me: do you work with *mitigation* or *adaptation?* I think that we have to work with both of them. The climate change is here and we simply have to cope with it. Even if all carbon emissions would be drastically reduced the climate change will continue for many decades, so we have to *adapt* to this fact. However, we have to start today to *mitigate* the carbon as well as the water footprints. Water operations can be made much more efficient, water use can be significantly reduced, once we become aware of our responsibility as users. Energy production can be realized with less water footprint and again we – the energy users – can reduce the energy need as well as the water need. As soon as we recognize that **water is energy** and **energy is water** we all can contribute to lessen the carbon footprint of water operations as well as the water footprint of energy operations.

Personally I have got a lot of experiences and inspiration via the International Water Association (IWA), an organization that brings together many thousands of professionals from more than 110 countries. As the editor-in-chief of the journals Water Science and Technology and Water Science and Technology/Water Supply during five years I acquired a wider perspective of the water issues than from only my specialist area. I have learnt a little bit of the huge water quality and water resource issues. This has influenced me and is another driving force to try to describe the challenges of water and energy. I also had the privilege to serve as the program chairman of the first IWA conference on Water and Energy, held in Copenhagen in 2009.

Having been a member of IEEE (Institute of Electrical and Electronics Engineers) for many years has given me insight what control, monitoring, drive systems and power systems technology and information technology can do to improve water and energy operations.

Preface 2nd edition

The manuscript of the first edition of the book was finished in early 2012. Since then there has been a tremendous increase of the attention to the water-energy nexus topic that makes some parts of the 1st edition look almost outdated in my view. Three and four years ago, when I talked about hydraulic fracturing or tar sand oil not many people were aware of the issues. Today a majority of people that I meet have become aware of these topics via newspapers, TV or other media. I have got a lot of constructive feedback, new insights and encouragement from readers, students, colleagues and audiences. All these factors have strongly motivated me to update and extend the book. Among the significant recent developments:

IPCC delivered the Assessment Reports number 5 in 2013–2014 with updated observations and predictions of climate change. A lot of new knowledge has been collected since the 4th Assessment Reports. The climate data inputs have been increased hundredfold in just a few years and the climate models have been refined. Climate change is real and the IPCC conclusions should be true wake-up calls. In 2014 we noted the Earth Overshoot Day on August 19, marking the date when humanity has exhausted nature's budget for the year. This is one day earlier than in 2013. For the remainder of 2014 we were living on resources borrowed from future generations. We have been operating in overshoot. In fact, since 2001, Overshoot Day has moved ahead by an average of 3 days per year.

New climate meetings were held in 2013 and 2014 in preparation for the important COP Paris meeting in December 2015. It is getting urgent to make real progress in the reduction of emissions.

IEA presented quite a dramatic and pessimistic view in the Energy Outlook in November 2013. If we do not make any drastic reduction of our consumption of fossil fuels the 2°C goal will be just an illusion. We are heading towards 4°C. This will become a different world altogether! The conclusions in 2014 are not less pessimistic. I have not heard a single politician making any comments about the threat of the 4°C. To risk that Bangladesh and the Pacific Islands will be flooded because of our fossil fuel consumptions is nothing less than a moral crime.

Hydraulic fracturing has taken off at a rate that was hardly possible to predict only a couple of years ago. It is now a controversial issue not only in the US, but also in China, Europe, South Africa, South America, to name a few. Hydraulic fracturing is no longer an obscure technical term that engineers use to describe a process first practiced in the US in the late 1940s. The political, environmental, social and economic consequences of the shale gas exploration are significant. So, when oil and gas are increasingly obtainable, what will happen with the transfer to renewables? Certainly, it does not help the climate work. Also, water becomes increasingly mis-used. The ambitions to explore the oil and gas in the Arctic Sea make the picture even gloomier. The environmental risks are exceptional and climate change will be accelerated. There are competitive alternatives to coal and other fossil fuels, but there are no alternatives to water.

From the Swedish radio news on January 6, 2015 we learnt that the oil price had dropped below US$ 50 per barrel. The startling comment was that ‘the consumption of oil is increasing but not sufficiently fast, since there is a surplus production’. This is our economic imperative: grow or die. Since the oil price has dropped there has been hardly any discussion of the consequences for the climate. Most of us are aware of climate change, but this does not change our life styles or the political agenda, even if the whole earth is threatened. What is wrong with us?

Coal burning has been in focus more than ever. In South Africa the completion of two huge coal-fired power plants have raised a lot of controversy. In China coal burning and coal mining has demonstrated two critical issues: (1) lack of water for coal mining and for cooling of power plants and (2) the air pollution problem becoming increasingly serious, most noticeable in Beijing. Last November the smog in Beijing delayed my flight arrival there for a full day.

Controversy is developing around hydro power. One is the amount of evaporation in warm countries. The other is the predicted environmental consequences for large scale development of hydropower, for example along the Himalayan slopes.

In the US the overall belief in climate change had its low mark in 2010–2011. The summer of 2012 was unusually hot in the US, offering an illustration of how energy, water and food are strongly related. Too little or too warm cooling water forced nuclear reactors to shut down. Serious drought made the corn harvest fail, clearly demonstrating the competition between corn (and land use) for food or for fuel. Today more than 75% of self-identified Democrats and liberals believe humans are changing the climate. On the other hand, self-identified Republicans mostly reject the scientific consensus. Similar rifts can be found in Canada. The same phenomenon is also documented in the UK, Australia and in Western Europe, according to a World Bank press release in November 2012.

The United States Climate Action report was released in May 2014, published by the US Department of State under the leadership of John F. Kerry, Secretary of State. This is a remarkable document where the nation states that the country is committed to doing its part of the climate work. Hopefully this report will change the debate in the US and influence the climate work also in other countries. President Obama’s Climate Action Plan raised the hope. Talks between the Presidents Xi from China and Obama from the US in Beijing in November 2014 were encouraging.

Yes, there are some positive technology developments. The efficiencies of a lot of equipment and industrial processes are improving all the time. Membrane technology is making tremendous progress and this will influence water treatment technology, including desalination. The cost of wind and solar photo-voltaic power is decreasing at an impressive speed, while the price for fossil fuel can only go upwards in the future, despite occasional price drops.

It is encouraging to watch the increasing interest in water and energy. The engagement among water professionals has been there for some years. Now also many energy operators and energy professionals consider the water-energy nexus is of great importance. New reports have been produced by UN, the US Department of Energy, as well as energy companies like BP. Water and Energy was the special theme for the 2014 World Water Day. I had the personal pleasure of taking part of the discussions both in Oslo and in Stockholm. Also the Stockholm World Water Week program in 2014 was composed around the water and energy theme.

The former director of the NASA Goddard Institute for Space Studies, Dr. James Hansen, gave a lecture a few years ago. He asked the audience: ‘What would you do if you know what

I know?' Behind him on the screen he showed pictures when he was arrested by the police during a climate demonstration outside the White House. Can a researcher balance scientific integrity with political engagement? Yes, I think it is both possible and necessary. As the author Roger Pielke discusses in his book 'The honest broker: Making sense of science in policy and politics' (2007) the researcher should have a role of 'honest broker', clarifying pros and cons of different actions instead of only presenting specific solutions. A truly scientific debate should not be mixed up with political conflicts. We should remember that behind every diagram or table or line of text there is not only numerous hours of work. It is also a human being: we are parents, grandparents, friends, family members or citizens. As a researcher I am also obliged to be a human. We have unmistakable indications that now is the time to make a change. Even small actions can make a big difference.

During the last few years I have become increasingly frustrated concerning the fossil fuel industry. Its economic power is monumental. Being the major commercial actor in many regions or even countries it also means that the fossil industry can preside over governments. About one-third of emissions are related to the top 20 corporations. It is not the corporations themselves that cause most of the emissions but the products, used for transportation, energy and heat generation, and industrial production. Fossil fuel exploration, refining and production not only affect our climate but also cause tremendous water quantity and quality problems. Hypocritical statements have been made by political leaders to support renewable energy, while subsidies for fossil fuels are an order of magnitude larger and increasing. The political influence of the fossil fuel industry cannot be overestimated; it supports too many politicians. It is logical that climate actions will be delayed. However, nature and the laws of physics are what they are – unbribable.

We cannot keep quiet when we study the devastating development of oil sand exploration in northern Alberta, when oil extraction delivers incomprehensible wealth from the Niger Delta while the local communities are left with environmental catastrophes, when millions on tons of oil are leaking into the Arctic Sea every year while the oil and gas industry prepares for oil exploration in these hazardous seas, when air pollution from coal burning kills millions of people, or when the poorest people are hit by the consequences of climate change. How would I explain to the children and the grandchildren that I saw the threat, but didn't speak up in time? We simply have to communicate the urgency of acting to avert potential disaster.

Our children will hopefully live towards the end of this century. I fear what they will witness. So, we have to bring them hope. New technology brings a lot promise but is not sufficient. We have to radically change our way of thinking how to use Mother Earth. We – not only all 'the others' – have to reduce our ecological footprint and reflect on what we eat, what we consume, how we travel, how we heat and cool our homes and how we use our hot water . It is a matter of solidarity with the rest of the members of our global family.

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A lot of people have been supporting, inspiring, and teaching me.

Bo N Jacobsen (European Environment Agency, EEA) and I cooperated to organize the first IWA conference on Water and Energy, held in Copenhagen 2009. Bo and the rest of the program committee gave me the real push to commit myself to this task.

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In Sweden I gained a lot of insight into energy issues in water and wastewater systems via the energy project initiated by the Swedish Water & Wastewater Association, in particular from Daniel Hellström, Anders Lingsten and Mats Lundkvist while I produced a Swedish report on energy issues in the water and wastewater industry.

Encouraged by the IWA interest in water and energy I started to collect ideas and learn more about the critical water/energy issues. In 2010 I presented a rough outline of a book to Michael Dunn, the Director of IWA Publishing (IWAP). He seriously encouraged me to write the book. Maggie Smith at IWAP immediately gave me a lot of support, encouragement and suggestions. Michelle Jones has taken care of all the details involved in the book production.

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Dr. Nenibarini Zabbey (University of Port Harcourt, Choba, Rivers State, Nigeria) has taught me a lot and revealed consequences of the arrogance and corruption in connection with large scale oil exploration in his home country. The environmental and human catastrophe as a result of the oil exploration in the Niger Delta is nothing less than a criminal act against a whole population. There is a formidable challenge in front of us to clean up.

Dr. Gianguido Piani was my co-author of a book Computer Systems for Automation and Control, published in English, German and Russian. Gianguido has worked in the energy sector for many years in Russia, Germany, Sweden and Italy. He has had a lot of influence on Chapter 4 on climate change and has taught me not only about climate change but also of the outcome of the climate meetings.

Since mid-2010 I have more or less lived with the book. It has been a fascinating learning process mixed with frustration and anger concerning the dramatic differences between the 'haves' and 'have-nots' and the arrogance of many industries and leaders.

Josef Lidbeck prepared all the maps. Sara Korsgren Norrby, my daughter, and her husband Johannes Norrby, have encouraged me a lot in the writing process. Above all, Kirsti, my patient, incomparable wife, miraculously loves me, keeps my sanity and lives with my odd habits of work. She has not only endured my work but has given me constructive feedback, never-ending encouragement and enjoyment.

This book is for my grandchildren – I hope that we will make a better world for you.

Göteborg
Sweden in March 2012
G.O.

Acknowledgements 2nd edition

During the last three years I have learnt a lot more about water and energy. So many people have educated me, inspired me from their publications, and shared their experiences. I have been inspired by students that have started to do research on the water-energy nexus to widen our knowledge.

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Since late 2012 I have been part of the International Steering Committee and later the International Technical Committee of the Water for Energy Framework (W4EF) under the leadership of Laurent Bellet together with Yann Lemoine, EDF, France. The project was launched following the 6th World Water Forum in Marseille (March, 2012). The goal is to produce a conceptual and analytical framework for the evaluation and reporting of the relations between energy activities and water. The results will be presented at the 2015 World Water Forum in Korea. The W4EF work has provided many new insights. In particular, I wish to thank Laurent for his valuable feedback and support.

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Together with Dr. Allan Hoffman (former Senior Analyst at the Department of Energy, Washington DC) and Andreas Lindström (SIWI) I have studied the environmental impact of shale gas exploration and hydraulic fracturing. We published a report on hydraulic fracturing at the Stockholm World Water Week in 2014. Allan and Andreas have inspired me and given me new insights in the water-energy nexus. Allan regularly supplies me with new information and shares his extensive experiences. Andreas is all the time working hard to make the water-energy issues visible and prioritized.

Dr. Nenibarini Zabbey, University of Port Harcourt (Nigeria) and Head of the Environment and Conservation Program at the Center for Environment, Human Rights and Development (CEHRD) is one of these heroes that don't give up. He has spent years to document the destruction caused by the oil spills in the Niger Delta and has been one of the experts that finally brought recognition to the Bodo Community. Only a few days before this manuscript has been sent to the Publisher Shell has agreed to compensate the Bodo community with 55 million pounds. This is far from sufficient to clean up in the Niger Delta, but it gives some hope for justice in the future.

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Göteborg, Sweden
January 2015
G.O.

PART I

Introduction

The water and energy interdependence

Water is essential for all life. There are no substitutes. Water is not renewable, so we have to take care of the same amount of fresh water that was available for the dinosaurs. So the water is reused. The problem is that a growing population, climate change, increasing standard of living, food production and industrialization will put a lot of pressure on water resources. Pollution and contamination of available fresh water sources will further decrease available water. Still we witness so much misuse of water. Too often it is considered to be ubiquitous and taken for granted and the water is not given its true value. Water is not just an environmental issue. It is a fundamental issue at the very heart of justice, development, economics and human rights.

As stated by the UN Committee on Economic, Cultural and Social Rights (2002):

> '. . . Water is fundamental to life and health. The human right to water is indispensable for leading a healthy life in human dignity. It is a pre-requisite to the realization of all other human rights.'

Water is certainly needed for life. Still it is a great killer. Floodings and contaminations kill millions of people every year. Most often we can do something about this. Water has been and still is a source of conflict between people, between regions and nations. Water can be considered synonymous with human power and influence. During the history the most powerful nations and kingdoms were established around fresh water sources – rivers or lakes. Civilizations have collapsed as a result of sustained droughts, exemplified by the Tang (907 AD) and Yuan dynasties in China, the Maya empire (900 AD) in Meso America and the Khmer Empire in Cambodia that peaked in the 13th century.

Energy is a fundamental condition for a decent life. Energy is needed to extract, treat and distribute drinking water as well as to collect and treat the wastewater. It is less apparent that energy depends so much on water. Water is needed to extract primary energy, to refine the fuel, and to generate electric power. Energy production also has a large impact on water quality.

> The fundamental difference between water and energy is that energy can be renewable while water resources are not.

Water and energy are inextricably linked and as a consequence both have to be addressed together. This is the **water-energy nexus** (a nexus is a connection or series of connections within a particular situation or system). Too often energy planners have assumed that they have the water they need and water planners have assumed that they have the energy they need. In Sweden and in many other countries energy and water issues are managed in separate government ministries. In Malaysia the water and energy issues are handled together in the Ministry of Energy, Green Technology and Water.

Water and energy are fundamental for **food production**. Even if this book primarily addresses the water-energy nexus the links to the food challenge must not be overlooked. Therefore we will shortly address the couplings between food, land use, water and energy.

Neither water nor energy is just one sector of engineering or science. They are fundamental to many sectors. Therefore we have to cooperate between disciplines to solve many of the problems related to water and energy.

Both water and energy infrastructures are expensive. In an industrialized country like my own Sweden roughly 55 billion Euros (€) have been invested over the years in power generation, transmission and distribution and about the same amount of money for water and wastewater systems. This means around € 6000 per capita for electric power and the same amount for water.

The water and energy nexus will be described in Chapter 1. The strong couplings between water and energy are also causing conflicts, and some examples are described in Chapter 2. As a result it is crucial to search for holistic solutions and integrate the various factors. This means that the water community and the energy community have to understand each other and cannot act independently of each other. This is discussed in Chapter 3.

1 The water and energy nexus

Water quality and water supply requires integrated action in the development, management and water usage.
Agenda 21, UN Conf. on Environment and Development (UNCED), 1992

Over the years I have worked with different aspects of control of water and wastewater systems as well as control of electric power systems. However, the starting point for me to realize the importance of the water-energy nexus came from a couple of papers from 2004 by Allan Hoffman, US Department of Energy. He subsequently generously offered me more information on the topic. The interdependence between water and energy has been more widely recognized during the last few years. Allan Hoffman (2004a) wrote on the topic:

> 'The energy security of the United States is closely linked to the state of its water resources. No longer can water resources be taken for granted if the U.S. is to achieve energy security in the years and decades ahead. At the same time, U.S. water security cannot be guaranteed without careful attention to related energy issues. The two issues are inextricably linked'.

He has later presented a lot of new findings (Hoffman, 2004b, 2006, 2008, 2010a, 2010b).
This statement is valid for a large number of countries. In the USA the Energy-Water Nexus initiative was initiated in 2004 as an informal DOE (Department of Energy) National Laboratory project to develop a better understanding of the link between the nation's energy and water supplies. The laboratories conducted preliminary assessments that indicated that the interdependence between energy and water supplies were much broader and much deeper than initially thought.

1.1 THE WATER AND ENERGY INTERRELATIONSHIP

The energy sector may be the largest water consumer among all industrial sectors. As long as there is a surplus of both water and energy we do not realize the close relationship between them. When any of them gets limited it becomes obvious that it is necessary to consider their interdependence. Most of us realize intuitively that water operations will require energy, Figure 1.1. It is less obvious that all energy production and generation also require a lot of water; for the extraction, refining, and electric power generation. As a consequence, water and energy systems and operations have to be planned together. Already there have been many negative consequences of water or energy systems being planned separated from each other.

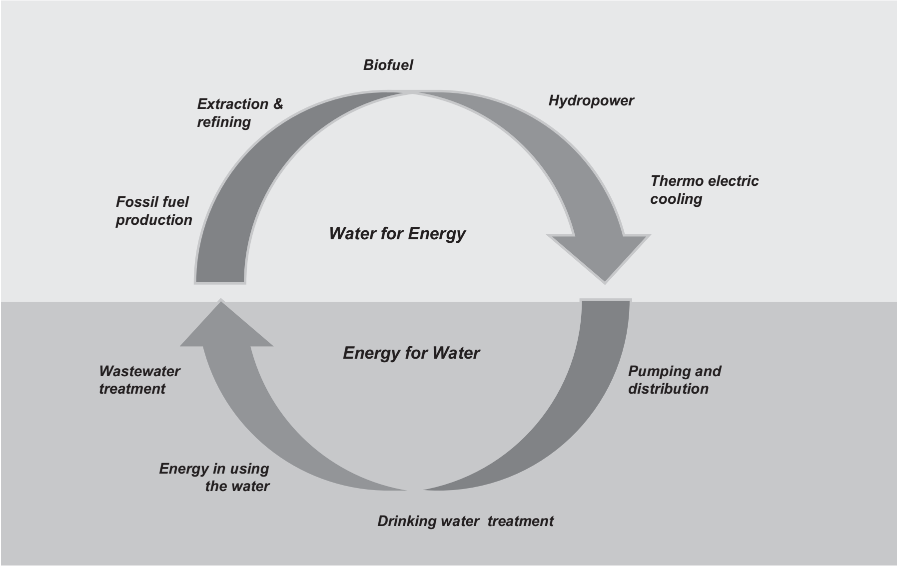

Figure 1.1 Water for energy – energy for water. Adopted from WEC (2010a). Water, Energy and Climate Change, WBCSD (2009a,b).

Population growth, climate change, urbanisation, increasing living standards and food consumption will require an integrated approach. The design of our cities, suburbs, homes and appliances has enormous implication for water and energy consumption. Also our attitudes and our life-style have a crucial impact on the water and energy resources. The water and energy consumption is more than an engineering challenge. Many non-technical issues have to be carefully studied. Some examples of the water and energy interdependence can be mentioned:

- Between 1% and 18% of the *electrical energy* in urban areas is used to treat and transport water and wastewater. The energy related to water use – mostly heating the water in households and industries – requires about ten times more energy compared to the energy needed to deliver the clean and cold water and to treat the wastewater.
- To *treat water* to drinking standards requires energy. As the raw water source becomes more contaminated traditional methods are no longer sufficient. More energy will be required to treat the water to drinking standards, using for example membrane technology.
- *Hydropower* generation obviously depends on water. The dam itself often serves as a gigantic sedimentation basin, and the silt brought by the river flow and that earlier served as fertilizer downstream now is trapped in the dam. Obviously the water flow downstream is affected. Increasing water shortage in combination with increased water use in many regions are now causing lack of water in the dams. With lower water levels the generation of electricity is decreasing.
- *Energy exploration and production* require a lot of water and consequently will generate a lot of wastewater. Oil, gas and coal exploration not only use a lot of water, but it also gets highly polluted and too seldom properly treated.

- Thermal power plants require huge amounts of *cooling water*. For example, around 40% of all freshwater withdrawals in the USA are used for thermoelectric energy production. This is roughly the same amount of water as for irrigation. Most of the cooling water is returned but around 3% is actually consumed, mostly by evaporation. The demand for cooling water competes with agriculture and municipal demands. As a result of the climate change many rivers are running drier and/or warmer in the summer. This will put a lot of constraint on energy production.

There are also indirect links between water and energy. Energy production and use often lead to contamination of underground and surface water supplies. The waterways for transport of goods may be limited if there are competing uses of the water. The interdependencies between water and energy should force us to conduct planning and operation in such a way that both the water and energy flows are tracked. Integrated systems analysis, integrated planning and inter-disciplinary cooperation will become increasingly important.

1.2 THE SUPPLY OF WATER

It is apparent that there has to be a balance between supply and demand of water resources. As a consequence, water scarcity not only appears in very dry countries but also in relatively wet countries. For example, we mostly think about England as a wet country. Still South-Eastern England suffers from water scarcity due to insufficient water transmission systems and to the region's huge ecological footprint. Water scarcity is fundamentally dynamic and intensifies with increasing demand and with decreasing quantity and quality of the supply. It can also decrease when the adequate response actions are taken. Water scarcity can be either *physical* scarcity or *economic* scarcity:

- *Physical* scarcity is related to availability of fresh water of acceptable quality with respect to the demand. Physical water shortage is the obvious example.
- *Economic* scarcity means that there may be water resources available, but there is not sufficient capacity to treat and distribute the water to the users. So, there is scarcity in access to water services. There can also be scarcity due to inadequate infrastructure, irrespective of the level of water resources, due to financial constraints.

Water scarcity can also appear in a 'wet' country when demand is much bigger than supply.

Economic development contributes to the rapid increase of water use.

> The water use has been growing globally at more than twice the rate of population increase in the last century. The world water demand has more than tripled over the past half century.

According to FAO AQUASTAT (2015), global water use in 2000 is estimated to have been about 30% of the world's total accessible fresh water supply. That fraction may reach 70% by 2025. The water use of the industry and households increased a factor of four during the second half of the 20th century. This increase is twice as high compared to the farming water use increase. At global level, the water withdrawals are 70% agricultural, 11% municipal and

19% industrial. These numbers, however, are biased strongly by the few countries which have very high water withdrawals. Averaging the ratios of each individual country, we find that 'for any given country' these ratios are 59%, 23% and 18% respectively. The ratios also vary much between regions. In South Asia the ratios are 91% for agriculture 7% for municipal and only 2% for industrial water withdrawals while in Western Europe the ratios are 8, 16 and 77% respectively.

> During the last 60 years the area under irrigation has doubled and the amount of water drawn for agriculture has tripled.

Obviously, the agriculture need varies significantly between regions. In a country with temperate climate and regular rainfall the water need may not be apparent. For example, in the UK agriculture requires around 3% of all water withdrawals. In the USA the corresponding figure is 41%, in China almost 70% and in India close to 90%, most of it for irrigation. The water need for food production will be discussed in Chapter 6.

Less than ten countries hold 60% of Earth's available freshwater: Brazil, Russia, China, Canada, Indonesia, the United States, India, Columbia, and the Democratic Republic of Congo. Other countries, all over the world, face water scarcity or water stress. China and India, with more than one third of the world population, have less than 10% of the world's freshwater. There are huge differences between different parts of these large countries. The average annual rainfall in the south-east of China is 110 times that in the western desert regions. Also within India there are similar large differences between wet and dry areas.

While **water scarcity** considers the natural allocation in relation to the number of users, **water stress** considers the fact that more people live in places characterised by either too much, too little, or the wrong quality of water. Australia, for example, faces the most acute water scarcity of any developed country. In regard to developing countries, India's chronic water scarcity problems will become an even bigger challenge over the next few years, as will the Middle East's and Africa's. Most countries in the world outside the Arctic zone, developed and undeveloped, and even a small developed country like New Zealand, face scarcity challenges in different parts of their geographies. A new high-tech city, Dubai, has been built in a desert and already has the world's highest per capita rate of water consumption.

1.2.1 Water and poverty

An increasing number of regions are reaching the limit at which water service can be sustainably delivered. The combination of demographic growth and economic development are putting an enormous pressure on renewable but finite water resources, especially in arid regions. According to UNEP (2010) available freshwater resources are declining.

> By 2050, 1.8 billion people will live in countries with 'absolute' water scarcity (<500 m^3 per year per capita), and water withdrawals will have risen by 50% in developing countries and 18% in developed countries. Two-thirds of the world population could be under 'stress' conditions (500–1000 m^3 per year per capita).

Human activities will also cause water quality to decline, polluted by microbial pathogens and excessive nutrients. There is also a rising concern about the impact of personal care products and pharmaceuticals.

The situation will be exacerbated as rapidly growing urban areas place heavy pressure on neighboring water resources. Further, the lack of access to clean water has major health implications.

> Globally, contaminated water remains the greatest single cause of human disease and death.

Some indications of the seriousness, according to WHO, UNICEF and WaterAid (www.wateraid.org), are:

- Globally 884 million people (one in eight) live without safe drinking water and 2.5 billion (two in five) do not have adequate sanitation. The lack of these basic services adversely affects people's health, education, dignity and livelihoods.
- Every day 4,000 children die needlessly from diarrhea, and countless others are too sick to go to school.
- Millions of hours are wasted as women and children walk each day to collect filthy water.
- With nowhere safe and clean to go to the toilet people are exposed to disease, lack of privacy, and indignity; problems which are particularly acute in overcrowded urban settlements.
- In schools without private sanitation facilities girls often drop out as they reach puberty.

> 440 million school days are lost because of water-and sanitation-related diseases.

> 4000 children dying every day would correspond to around ten jumbo jet crashes per day, and the majority of the passengers are children.

- Nearly 4 billion cases of diarrhea occur each year;
- 200 million people in 74 countries are infected with the parasitic disease Schistosomiasis;
- Intestinal worms infect about 10% of the population in the developing world. Intestinal parasitic infections can lead to malnutrition, anaemia and stunted growth;
- It is estimated that 6 million people are blind from trachoma, and that the population at risk is 500 million.

Poverty is closely related to lack of access to clean water.

Lack of access to water is one of the defining criteria of poverty and consequently access to clean water is now recognized as the key to poverty reduction.

1.2.2 The millennium development goals

The Millennium Development Goals (MDGs), a series of targets for reducing social and economic ills, were articulated in 2000 by the UN. In 2015 the MDG should improve the existence of many and save the lives of those threatened by decease and hunger. In the UN report for 2014 important progress was reported UN MDG (2014) and many goals had actually been met. One of the targets was halving the proportion of people who lack access to improved sources of water.

Access to an improved drinking water source became a reality for 2.3 billion people between 1990 and 2012. In 2012, 89% of the world's population had improved water available. This means that still some 800 million people lack clean water, even if UN claims that the MDG target has been met.

UN declares that over a quarter of the world's population has gained access to improved sanitation since 1990, yet a billion people still resorted to open defecation. Between 1990 and 2012, almost 2 billion people gained access to an improved sanitation facility. However, in 2012, 2.5 billion people did not use an improved sanitation facility and 1 billion people still resorted to open defecation, which poses a huge risk to communities that are often poor and vulnerable already. Much greater effort and investment will be needed to redress inadequate sanitation in the coming years.

Global emissions of carbon dioxide (CO_2) continued their upward trend and those in 2011 were almost 50% above their 1990 level. Millions of hectares of forest are lost every year, many species are being driven closer to extinction and renewable water resources are becoming scarcer.

The UN Human Rights Council passed a resolution 7/23 on March 21, 2008. The Council was concerned that climate change poses an immediate and far-reaching threat to people and communities around the world and has implications for the full enjoyment of human rights. It also recognized that climate change is a global problem and that it requires a global solution. Viewing at the IPCC findings through a human rights lens, it was clear that climate-change related effects threaten the effective enjoyment of a range of human rights:

- The right to safe and adequate water and food;
- The right to health and adequate housing.

The Council also emphasized that the human rights perspective brings into focus that climate change is set to hit the poorest countries and communities the hardest.

According to UNSD (2015) and UN MDG (2014) nearly 80% of the unserved population is concentrated in three regions: sub-Saharan Africa, Eastern Asia and Southern Asia. Coverage is above 78% in all regions except sub-Saharan Africa and Oceania where it amounts to 56% and 50%, respectively. While 80% of the developing world population have access to some type of improved drinking water source, only 44% have access through a household connection from a piped system. Although access to improved drinking water is currently above 80% in Southern Asia and South-eastern Asia, levels of coverage through household connections are only 20% and 28%, respectively, not much above the level of 16% in sub-Saharan Africa.

In September 2011, the Human Rights Council adopted its 3rd resolution on 'human rights and climate change', resolution 18/22. The resolution was tabled by the Philippines and Bangladesh and supported by 43 other countries, among them the Maldives. The resolution affirmed the human rights obligations. The results were presented at a seminar in February 2012 in Paris and the report was available for the COP18 meeting in Doha, Qatar, in December 2012. More on the COP meetings is presented in Chapter 4.

So, what is meant by 'human right' to water? According to UNDP and WHO it includes:

- Between 50 and 100 liters of water per person per day to ensure most basic needs;
- The water source has to be within 1 km from home;

- Collection time should not exceed 30 minutes;
- Water cost should not exceed 3% of household income.

1.2.3 Energy supply for water

Part of the effort must be spent on the energy that is required to provide safe drinking water and some adequate sanitation, especially in the urban areas. Obviously, institutional and economic actions are needed, and the technical solutions have to consider the particular needs for the poor people. As stated by the WHO and Unicef (www.unicef.org), the distance to the drinking water tap has several implications: '*An important aspect must be considered in this analysis: the type of access to improved drinking water. … The availability of drinking water within the household through a household connection provides a better level of service. For example, it allows the use of drinking water in quantities that would normally fulfil the health and hygiene requirements of the householders. Where a drinking water source is not available within the property it is likely that they will not use more than the very basic quantities required for hygiene, drinking and cooking (20 liters per capita per day).*'

Energy is a pre-requisite for water availability.

The climate change threatens to make the situation worse. Fossil water – water in aquifers that is not replaced – is disappearing with an alarming rate. Glaciers are melting and many rivers never reach the sea.

1.3 EXPEDIENTS FOR WATER

> *Action expresses priorities.*
>
> Mohandas Gandhi

1.3.1 The value of water

Adam Smith (1723–1790) in *Wealth of Nations*, published in 1776, once posed an intriguing question: 'Why is water, which is essential for life, so cheap while diamonds which are nothing more than pretty stones so expensive?' It took a long time to find a proper explanation, and this has to do with the difference between 'total' value and 'marginal' or 'incremental' value, in other words the value of the next unit being used.

Consider a fixed amount of water to be used for the next month. We would first set aside the water for survival. After that we may use the water for personal hygiene. After that maybe for washing the dishes, and then cleaning the house. For each new use the additional value of water becomes less. The least prioritized use may be water for watering the lawn or washing the car. If the total amount of available water would decrease we will most probably not make an equal proportional reduction in water for survival and water for the lawn sprinklers. We would reduce the least valuable water use and keep the water for survival. The *marginal* value for water is very low if it is not for survival. However, the *total* value of the water is high, since it includes the water for survival. The marginal value may be the reason why we are not willing to pay the adequate price for water, as long as we have plenty of water.

The value of water has to be reconsidered.

Diamonds are not essential for life and have a low total value. However, because we do not have plenty of them their *marginal* value is high. The next diamond we buy is a marginal purchase and is valued very high. So diamonds have a high marginal value but a low total value and it is the marginal value that determines the price. This is the explanation of the paradox stated by Adam Smith. We know that we would trade our diamonds for water if we would need the water to survive the next hours or days.

When water supplies are abundant their value is low. It may seem that we have an infinite supply and there is no need to worry. However, as we approach depletion, even small perturbations due to unforeseen climatic events, sharp increases in demand or technical malfunction result in disproportionate changes in their values and prices, if the market is allowed to work. As a result the total value (price · quantity) rapidly increases as total quantity declines. This is true for any resource that is essential and non-substitutable. As there is less water or energy available, their price quickly increases. This can create havoc in markets and stress the whole economic system. Diminished water supplies may lead to direct conflict and violence. This is further discussed in Chapter 2.

1.3.2 Economic and energy resources for water

Considering the importance of the topic it is interesting to examine how much resources have been spent on water research. The situation in the United States is interesting and may illustrate the more general situation. Since 1973, the population of the US has increased by 26%, the GDP and federal budget outlays have more than doubled, and federal funding for all research and development has almost doubled, while funding for water resources research has remained stagnant. Funding for water supply augmentation and conservation, water quality management and protection, and water resources planning have severely declined since the mid 1970s. Still, the pressure on water resources increases with population and economic growth.

There is an increase in the number of conflicts over water, so there are strong incentives to focus much more on the water and energy issues, both in many parts of the industrialized world and in the developing world.

When the energy supply of non-renewable fossil fuels is depleted we are looking for renewable sources. Similarly, we are over-utilizing fresh water resources in many places. This is compensated by increasing the energy use to import water from other basins by pumping long distances, desalinate sea water or reuse wastewater. Furthermore, nonrenewable water is depleted by over-pumping from fossil aquifers. These practices are not sustainable and will leave our children with fewer options. We need to think much more in terms of increased efficiency and conservation.

In Europe a long term strategy for a European sector has been developed by the Water Supply and Sanitation Technology Platform (WssTP). The outputs in terms of Strategic Research Agendas are aiming to mobilize public and private bodies of all sizes to develop the water sectors and to create synergies between existing water organizations.

In July 2010 the United Nations General Assembly declared that access to clean water and sanitation is a human right essential to the full enjoyment of life and all other human rights. The 192-member Assembly also called on UN Member States and international organizations to offer funding, technology and other resources to help poorer countries scale up their efforts to provide clean, accessible and affordable drinking water and sanitation for everyone. The Assembly resolution received 122 votes in favour and zero votes against, while 41 countries abstained from voting, among them my own nation Sweden as well as the US, UK and Australia. On that day I was embarrassed and upset.

The text of the resolution expresses deep concern about all the people that lack access to safe drinking water and basic sanitation. The various users of water (people, agriculture, industry and nature) have to make sustainable use of the water resources without disturbing the balance, by not using more water than is needed or using water of a higher quality than needed quality.

1.4 QUANTITY AND QUALITY

For both energy and water both quantity and quality matter.

> **Water quality** is measured by the concentration of impurities, constituents dissolved or suspended in the water, as well as by its physical characteristics, such as colour and temperature.

Water quality can be significantly affected by energy-related projects. For example, water used for cooling purposes in power stations is returned to the river with a higher temperature, which may prove detrimental to some fisheries (Chapter 13). Hydropower that requires dams can also significantly affect physical and chemical parameters of water (Chapter 10). Mining may destroy whole landscapes, including streams (Chapter 11).

We use one kind of energy to produce other forms of energy of higher quality. Low density solar energy is abundant but hard to use. In photosynthesis solar energy is accumulated in woody biomass that can be then be used as a source of energy of higher quality. With photovoltaics (solar PV) we can convert solar energy directly into electricity, which is of higher quality energy than biomass. If we need to use energy to produce a different type of energy of the same quality, we lose efficiency. The higher the quality, and the more efficient a water or energy supply is, the more reliable and the easier it is to provide to end users. This is further discussed in Chapter 15.

> *Quality of energy can be expressed as efficiency, reliability, and continuity of supply.*

As demand for water grows, there will be more competition with regard to water needed for energy production. If water becomes as limiting as energy, there will be more pressure on water-intensive energy producers to seek alternative supplies.

The links between water and energy are also becoming apparent by the frequent inefficiency and wastage in the way that both resources are used. There are serious inefficiencies in many parts of the world in electricity generation, transmission, distribution and usage. Likewise, there are inefficiencies and leaks in water distribution systems. It follows that substantial efficiency gains in water use will reduce electric power requirements, which in turn will lead to more savings of water that otherwise would be used in power generation.

A simultaneous analysis of water and energy use at the planning stage can enable significant increase in productivity in the use of both resources. Water conservation can lead to large energy savings and energy efficiency approaches will have an impact on water.

1.5 CHAPTER SUMMARY

- All water operations require energy.
- Energy production and generation require water; for the extraction, refining, and electric power generation.
- Water and energy systems and operations have to be planned together.
- Water scarcity is a reality for too many people, not only in dry countries but also wherever demand is much higher than supply.
- The value of water is often not appreciated and is often not reflected in the price or in the resources devoted to water research.
- The contamination of water resources further reduces available water supplies.

1.6 MORE TO READ

The books Diamond (2005, new edition 2011) and Pearce (2006) were real eye-openers for me. Diamond analyzes the reasons for the collapse of human civilizations in history, which relates directly to the issues of water, energy and food. Pearce gives a horrifying account of the damage caused by mankind to its rivers. Still, the books give some hope, but this would require that the world begins to think differently about water.

The water-energy nexus is described by Cohen (2007) and in some articles in a special issue of Southwest Hydrology (2007). Pate *et al.* (2007) provide an early overview and the textbook Gautier (2008) is an excellent introduction into this extremely complex topic of water, climate and energy interactions. The paper by Webber (2008) is an excellent introduction into the water-energy nexus. In recent years the water-energy nexus has been topic for an increasing attention, such as the UN report UN WWDR (2014), the BP supported work Williams-Simmons (2013), the World Bank report World Bank (2013) as well as the World Energy Outlooks, presented every year by IEA, the International Energy Agency (IEA, 2012, 2013a, 2014c). Naturally the IPCC Assessment Reports contain a lot of information on the water-energy nexus. This is further discussed in Chapter 4.

The books by Solomon (2010) and Fagan (2008) give fascinating descriptions of the importance of water within history. The books by de Villiers (2001), Bell (2010) and Fishman (2011) are recommended reading to get an appreciation of the water scarcity problem in the world today. The book by Chellaney (2011) is an insightful analysis of the water situation in Asia.

The US Department of Energy provides important sources of information for US water and energy uses (see DOE reports in the Bibliography). FAO, the UN Food and Agriculture Organization, (FAO AQUASTAT, 2015) provides a wealth of information on population, energy, water on the global scale. The increasing scarcity of water has been given much attention at the World Water Forums (from, 1997 and every 3 year). Special workshops and conferences with the water/energy theme have been arranged, such as IWA (2008, 2009, 2010).

Some water data are obtained from WBCSD (2009), CIA (2011), and the most recent Global Environment Outlook (GEO4) from UNEP (2010). The water-energy nexus is formulated in an appeal to the world's decision makers in IWA (2010).

Webb-Johnson (2009) and Voinov-Cardwell (2009) discuss water and economy, with special attention to the US. Farley-Gaddis (2007) describe price elasticity or the opposite for water. The European Water Supply and Sanitation Technology Platform (WssTP), where the author was part of one of the committees, is documented in WssTP (2006). WssTP (2011a) has a special emphasis on the research needs for water and energy.

The online newsletter Water 21 Global News Digest (IWA Publishing) regularly informs about water and energy related issues.

1.6.1 Journals

IWA publishes several journals relevant for the water and energy nexus, see www.iwaponline.com. In particular Journal of Water & Climate and Water 21 but also Water Science and Technology, and Water Science and Technology – Water Supply regularly contain articles on our water supply and relations to energy. IEEE journals like IEEE Spectrum, Control Systems Magazine, Instrumentation and Measurement, Sensors Journal should be of interest for water professionals. More journals are listed at www.ieee.org.

1.6.2 Visual media

Among all films and videos on the environmental theme I wish to recommend one film, called Home. It is freely available on YouTube. It is a magnificent documentary of life on Earth and shows the apparent couplings between food and the use and misuse of water and energy. Access www.youtube.com/movie?v=jqxENMKaeCU (latest access 15 Jan. 2015). Looking at the 1.5 hour video is well spent time.

2 Competition and conflicts between water and energy

> *If there is a political will for peace, water will not be a hindrance.*
> *If you want reasons to fight, water will give you ample opportunities.*
> Uri Shamir, Israeli hydrology professor

UN figures suggest there are around 300 potential conflicts over water around the world, arising from squabbles over river borders and the drawing of water from shared lakes and aquifers. Global climatic changes make water supply and demand more problematic and uncertain. Where water is scarce, competition for limited supplies can lead nations to see access to water as a matter of national security.

The water sector is facing a dramatic evolution because of three major 'drivers': the population growth, the urbanisation together with an aging and deteriorating infrastructure, and the climate change.

- *Population growth*: The globalization and population growth are enforcing rapid changes (migration, urbanisation, industrial activities, patterns of food production) leading to a dramatic increase in high-quality water consumption. Frequently, this demand for water cannot be satisfied by the locally available water resources, while the discharge of insufficiently treated wastewater increases costs for downstream users and has detrimental effects on the aquatic systems (see Chapters 5 and 6).
- *Urbanisation*: many existing infrastructures are aging and deteriorating. Both the rapid *urbanisation* and the *rural and under-developed areas* have to be considered carefully. In particular the urban systems will also see extreme events and recovery has to be part of the planning, see Chapter 5.2.
- *The climate change*: the climate change is predicted to cause significant changes in precipitation and temperature patterns, affecting the availability of water. So we will face increasing water stress and water costs as well as more extreme events. Extreme draughts as well as extreme flooding are expected to become more common. This is further discussed in Chapter 4.

2.1 CONFLICTS OVER SHARED WATER AND ENERGY RESOURCES

> *We must buy our own water to drink, our own wood can only be had at a price.*
> Lamentations, 5:4

Many rivers, lakes and groundwater aquifers are shared by two or more nations. This geographical fact has lead to disputes over shared waters like the Nile River in Africa; Jordan, Tigris and Euphrates in the Middle East; Indus, Ganges and Brahmaputra in the South Asia; Mekong in South East Asia; Danube and Rhine in Europe; and the Colorado, Rio Grande and Paraná in the Americas. The history of water related conflicts in the Middle East extends back 5000 years.

EXAMPLE 1: KOREAN AND PERSIAN GULF WARS

Hydroelectric dams have been the targets for many military actions during the last century, affecting both water and energy supplies. The dams on the Yalu River, forming the border between North Korea and China, were bombed during the Korean War in the 1950s. Iran claimed to have blacked out large portions of Iraq in July 1981 by bombing a hydroelectric dam in Kurdistan (New York Times, 20 July, 1981). In the 1991 Persian Gulf War most of Kuwait's desalination capacity was destroyed by the retreating Iraqi army.

EXAMPLE 2: NORTH KOREA

A strange variation of a hydroelectric conflict was discovered in 1986. North Korea announced plans to construct the Kumgansan hydroelectric dam on a tributary of the Han River that flows into Seoul in South Korea. The Kumgansan – later renamed *Anbyon – Power Station* aimed to create a total generating capacity of 810 MW in generators located at one site. In 1996 the DPRK completed the *Anbyon Power station*. The fear in South Korea was not only to get its water supplies disrupted, but the dam could be used as an offensive weapon. In a conflict the North Koreans could destroy the dam and flood Seoul downstream. This would create a tsunami of 50 m high waves in the Han River, as it flows through the city. As a result South Korea constructed a series of levees and check dams upstream of Seoul to protect the city (Hecker-Rota, 2000).

EXAMPLE 3: MIDDLE EAST – THE EUPHRATES RIVER

The Euphrates River flows from the mountains in southern Turkey through Syria into Iraq and ends up in the Persian Gulf (Map 2.1). Both Syria and Iraq depend heavily on the river for water supply, irrigation, industrial use and hydroelectric power. The rights of the water from the rivers have been a source of conflict between the three countries, further amplified by ethnic conflicts and historical memories. Turkey states that it has the authority over any water originating within its borders and the Turkish claims could be summarized as 'the water is as much ours as Iraq's oil is Iraq's'. The Euphrates and its tributaries are Syria's major water source, while Iraq downstream is dependent on both Euphrates and Tigris Rivers. Thus, any actions upstream are considered with great attention. In 1974 Iraq threatened to bomb the al-Thawra Dam in Syria with the motive that the dam had decreased the flow into Iraq. Later on Turkey has presented plans to build hydroelectric dams that could also be used for irrigation purposes, see Chapter 10. Using water as a weapon was practiced by Turkey in the mid 1990s when Syria was threatened to have the water flow cut off. The reason was that Syria supported the Kurdish rebels operating in the southern Turkey. Using the 'water weapon' against Iraq was also discussed during the Persian Gulf War when Iraq invaded Kuwait. This is a classic case of water quantity issue, and use of the available water in the basin. As noted in Example 1, Iraq destroyed much of Kuwait's desalination capacity during the retreat. More details are found in Just-Netanyahu (1998), De Villiers (2001), and in Gleick (2008).

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Map 2.1 The Euphrates and Tigris river basins.

EXAMPLE 4: CENTRAL ASIA

The destruction of the Aral Sea was caused by heavily diverting water from the Amu Darya and Syr Darya rivers, running westwards from the Himalayas to the Aral Sea (Map 2.2). This was earlier an internal Soviet problem, but now it has become an international conflict that affects six different countries. The Syr Darya in the north runs from Kyrgyzstan through Uzbekistan and Kazakhstan and the more southern located Amu Darya from Tajikistan through Uzbekistan and Turkmenistan. The Amu Darya and its tributaries form part of the border between the Central Asian states and Afghanistan.

Map 2.2 The Amu Darya and Syr Darya river basins.

Water use has increased rapidly since the Central Asian states became independent in 1991 and is now at an unsustainable level. Irrigation systems have decayed so severely that half of all the diverted water never reaches crops, and several years of drought have cut available water by a fifth even as demand continues to soar. Efforts to rebuild Afghanistan will now put yet more strain on supplies.

Water use for agriculture, industry and homes upstream will of course affect the water supplies downstream. During the Soviet time the two rivers were coordinated and operated as one huge river basin. Now the river management is fragmented and has become an un-coordinated competition between the upstream countries in the east (Kyrgyzstan, Tajikistan and Afghanistan) and the downstream countries in the west (Kazakhstan, Uzbekistan, and Turkmenistan). As a result the water use and energy generation are not operated in an efficient manner. The main reason for the conflict is the demand structure for energy and water resources, both in space and in time. In Kyrgyzstan and Tajikistan water is released in the hydropower dams during the winter in order to generate electrical power for heating. There the hydropower is by far the cheapest source of energy. The increasing winter flows will increase the risk for flooding downstream. During the warm summer months the upstream countries want to save water in the reservoirs to be prepared for the next winter hydropower generation. However, in the summer the downstream countries have the most urgent need for irrigation water. In this region, cotton is an important crop and wheat is considered essential to meet national food security goals.

During the Soviet time the river basins were operated to provide irrigation and to maximize the crop production. Part of the hydropower was used to supply all the pumps downstream for irrigation. In return the upstream countries got gas and coal deliveries to cover the energy requirement for the winter. Just-Netanyahu (1998), De Villiers (2001), World Bank (2011b), and Bernauer-Siegfried (2012) are key sources of information on Central Asia.

EXAMPLE 5: SOUTH ASIA – THE INDUS RIVER

The Indus River (Map 2.3) is born in the Himalayas and flows to the Arabian Sea over the course of some 2900 km through India and Pakistan. With a basin coverage area of over 900,000 km^2, the Indus has a flow volume twice that of the Nile River, and three times that of the Tigris-Euphrates River system. One of the perennially important environmental issues is the scarcity and sharing of fresh water resources between India and Pakistan. Before flowing to the vast plains the river is harnessed for hydroelectric power, currently at levels far below their maximum potential.

The problem of water resource allocation and sharing, primarily for irrigation purposes, has plagued relations between India and Pakistan. This has led to a true case example of environmental security where environmental issues are entwined with national security issues. The presence of this enormous population has exerted extreme pressures upon the environment and will continue to do so with the current and projected high population growth rates. A major source of conflict is the hydroelectric power on the India side. India claims that it will not decrease the available flow to Pakistan, where the irrigation from Indus is crucial. Pakistan, on the other hand, argues that India can stop the river flow and cause great damage to the agriculture in Pakistan.

The Kishanganga Hydroelectric Plant is part of a hydroelectric scheme that is designed to divert water from the Kishanganga (Neelum) River to a power plant in the Jhelum River basin. Construction on the project began in 2007. Pakistan is worried that the project will

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have adverse impacts on the flow of the river, which flows into their country and meets with the Jhelum River. Following a complaint by Pakistan the International Court of Arbitration (ICA) ordered India to cease construction of the Kishanganga hydropower project, which it concluded is in violation of the 1960 Indus water treaty. Pakistan is constructing the Neelum–Jhelum Hydropower Plant downstream of the Kishanganga. India states the Kishanganga project will divert 10% of the river's flow while other estimates stand as high as 33%. The ICA gave its 'final award' on December 20, 2013, wherein it allowed India to go ahead with the construction of the Kishanganga dam. The 'final award' specifies that 9 m^3/s of natural flow of water must be maintained in Kishanganga river at all times to maintain the environment downstream. The conflict is described well in Wikipedia.

Map 2.3 The Indus river basin.

EXAMPLE 6: SOUTH AMERICA – THE ITAIPÚ DAM ON THE PARANÁ RIVER

The Itaipú dam is the second largest hydroelectric plant in the world, generating around 12,600 MW (Map 2.4). It supplies Sãn Paulo and Rio de Janeiro with electrical power. It was jointly built by Paraguay and Brazil and was completed in 1991. Most of the electrical power goes to Brazil. In 2000 Itaipú alone provided 20% of the energy supply in Brazil and 94% in Paraguay. The land, where the Itaipú dam now sits, was once a source of great controversy between Brazil and Paraguay. Each nation declared rights and legal authority over the Guaira Falls, which lies on the border of both countries and to which both claimed ownership and control. In 1957, Brazil, who believed the Falls to be within their borders and who wanted to

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invest in the hydroelectric power of the Falls, unilaterally took military control over the region. After five years of dispute and disagreement, Brazil and Paraguay finally negotiated the terms of the Itaipú dam.

Map 2.4 The Paraná river basin.

Effects of the dam construction caused changed flow patterns downstream, which caused a conflict that had to be negotiated between Argentina and Brazil. Argentina had wanted to build its own hydroelectric dam in the Paraná downstream of Itaipú, but this would have influenced the operation of the Itaipú power plant. The Yacyreta Treaty, an agreement between Argentina and Paraguay, to construct a hydroelectric dam downstream from the Itaipú, has not been deemed as successful in its implementation. The project has been unable to fill the reservoir to planned levels, and is operating at only two-thirds of its capacity because of the environmental repercussions the system would incur if it was at 100% capacity (Wolf-Joshua, 2011).

EXAMPLE 7: USA (MAP 2.5)

An increasing number of water disputes are taking place as well in the eastern USA:

- Between Virginia and Maryland, Virginia and North Carolina, and among Georgia, Florida and Alabama;
- Competition for fresh water is already limiting energy production. For example, Georgia Power lost a bid to draw water from the Chattahooche River (Miami Herald, February 2002);
- The Environmental Protection Agency ordered a Massachusetts power plant to reduce its water withdrawals (Providence Journal, RI, July 2002);
- Idaho has denied water rights requests for several power plants (U.S. Water News Online, August 2002);
- Duke Power warned Charlotte, North Carolina to reduce its water use (The Charlotte Observer, NC, August 2002);

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- A Pennsylvania nuclear power plant is planning to use wastewater from coal mines (The Philadelphia Inquirer, July 2003). Other utilities are warning of a power crunch if water availability is reduced (Greenwire, July 2003).

Map 2.5 The United States (selected states).

In response, the Electric Power Research Institute (EPRI), the research and development arm of the private electric utility sector, has initiated a major new research program that will address the connection between fresh water availability and economic sustainability. As a first step, EPRI, which has projected that the world will need 6–7,000 GW of additional electrical generation capacity by 2050 (today's total is about 5,000 GW, see Chapter 9), undertook a screening study aimed at characterizing the probable magnitude of the quantity of water demanded and supplied, as well as the quality of such water, in the USA for the next half century (2000–2050). This screening study, published in 2002, concluded that '. . . water availability can severely constrain electricity growth.'

As pointed out by Allan Hoffman (2004a, 2004b):

> 'many Federal agencies address water issues, but none at the water-energy nexus. There is no Federal agency is responsible for water-related impacts on energy policy, for water used by energy production or for energy used by water systems'.

EXAMPLE 8: THE NILE RIVER BASIN

The Nile River (Map 2.6) has since the time of the Pharaohs been the paramount factor governing the destiny of Egypt. The prophet Isaiah (19: 5–8) wrote 2700 years ago: *The* *waters of the Nile shall drain away, the river shall be parched and run dry; its channels shall stink, the streams of Egypt shall be parched and dry up; reeds and rushes shall wither away; the lotus too beside the mouth of the Nile and all that is sown along the Nile shall dry up, shall be blown away and vanish. The fishermen shall groan and lament, all who cast their hooks into the Nile and those who spread nets on the water shall lose heart*.

Map 2.6 The Nile river basin.

The Aswan Dam, completed in 1971 (see Chapter 10) has changed the river and the regions around it dramatically (De Villiers, 2001). The Nile below the Aswan is now a totally managed irrigation channel. However, all the Nile water originates in other countries. Still Egypt consumes a huge share of the Nile basin water. The biggest source of the Egypt water is Ethiopia. The Blue Nile, Atbara and Sobat rivers supply some 85% of the water. Still Ethiopia and the White Nile River countries of East Africa, including Sudan, have been able to use only a tiny fraction of the Nile River water, but are now determined to increase their share. The Nile Water Agreement of 1959 basically divided the water of the Nile between Egypt and Sudan. Egypt got around 75% and Sudan almost 25%. The agreement totally neglected the claims from Ethiopia, Kenya, Tanzania, Burundi, and Rwanda. Ethiopia got some 1% of the Nile water. Egypt simply threatened with military actions to protect its water interests. In 2005 the Ethiopian Prime Minister Meles Zenawi was angrily protesting Egypt's monopoly on large scale Nile irrigation and threatening to unilaterally divert the river water within Ethiopia. Ethiopia has developed only some 3% of its hydropower potential.

The Nile River basin is a hydrological time bomb. There is only one reasonable solution: increase the efficiency of the water use and cooperate between all Nile River Basin nations to sustainably extract water from the Basin. Transboundary water management (TWM) could be used as a tool to reduce poverty. The underlying assumption is that in any given river basin there are different levels of power among riparian states. According to SIWI (the Stockholm

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International Water Institute) it has been shown that in regions where the basin hegemon has enabled 'positive' interaction between the actors, approaches to both influencing and challenging power asymmetry have been shown to have some degree of success (see also Kim-Glaumann, 2012).

The next serious source of conflict in the Nile River Basin is the Grand Ethiopian Renaissance Dam's (GERD). Ethiopia began constructing the dam in 2011, and since then Egypt and Ethiopia have been locked in a diplomatic dispute, which reached a peak in 2013. Egypt claims that GERD's high storage capacity will affect its national water security. Egypt has asked Ethiopia to reduce the dam capacity, finding it 'unjustified and technically unacceptable' (Egypt Daily News, 15 Jan. 2015). The three countries involved in the GERD project – Egypt, Ethiopia, and Sudan – are facing difficulties in technical negotiations. Egypt, which utilizes more Nile water than any other country, fears the dispute will have a detrimental effect on its share of Nile water. As per agreements signed in 1929 and 1959, Egypt annually receives 55.5 billion m^3 of the estimated total 84 billion m^3 of Nile water produced each year, with Sudan receiving 18.5 billion m^3.

The Nile River issues are further decribed in Sections 10.1, 10.3 and 10.4.

2.2 PRIMARY ENERGY SOURCES

It is often not understood or known that huge amounts of water are required to produce the primary energy sources like oil, gas, coal and uranium. The consumption of water to produce biofuel is even bigger, much bigger.

> According to IEA statistics more than 80% of the world's energy supply still comes from fossil fuels – oil, natural gas and coal. About 6% is nuclear and barely some 14% is the 'rest', meaning hydro, biofuels, refuse, sun, wind and other renewables.

Almost all extraction of primary energy requires water.

Water is needed for the oil extraction and as the age of the oil well is increasing more water is needed. Water or steam is injected into the well to enhance the oil extraction. The water use in oil sand extraction is huge since the oil and the soil have to get separated. Coal mining requires large amount of water. Additional water is needed for the refining processes.

In quite a few primary energy extraction and refining operations water quality will be significantly changed. It is only in a minority of the cases that the wastewater is treated to an acceptable quality. Naturally this has an impact on the environment and on groundwater quality but also on water availability in water scarce regions.

Burning fossil fuel has to decline due to its effect on the climate, and nuclear power will do the same because of the risks. Already Germany is moving away from nuclear power.

While large corporations battle to find new energy sources there are increasing activities to develop more sustainable processes, making existing energy consumption in industries, home and buildings more efficient. It is possible to use the heat content in lakes or in wastewater to heat buildings and the cool temperatures of lakes and other waters to cool buildings as a more sustainable air conditioning. One saved kWh ('Negawatt') is cheaper than producing a new one. The water use for energy production and generation will be discussed in detail in Part Three of the book.

2.3 ELECTRICAL ENERGY GENERATION

In Section 2.1 a number of conflicts related to energy and water have been described. Hydropower is often considered as 'green' energy in the sense that the electric energy production does not generate any emissions of greenhouse gases.

> Hydropower now generates about 16% of the world's electrical power. Only 2% of the global hydroelectric production comes from Africa, having 14% of the world's population. As a contrast almost 30% comes from North America, with only 6% of the global population.

These differences are not only a result of water availability but also show the difference in capital availability, technology, know-how and government efficiency.

> Reservoirs needed for hydropower generation globally cover a surface area of about 500,000 km^2.

The reservoirs needed for large hydropower plants globally cover a surface area of around 500,000 km^2 – roughly the size of Spain. With a lot of hydropower in warm countries there is a huge loss of water due to evaporation. The social cost is also significant.

> Around 80 million people have been forced to move due to dam constructions.

Hydropower will be further discussed in Chapter 10. The problems of evaporation are also dealt with in Chapter 7.

Thermal power plant operations – both coal fired and nuclear – require large amounts of cooling water, as will be explored in Chapter 13. Heating of the cooling water and the risk of radioactive contamination present environmental challenges. Addition of chemicals, for example inhibitors, anti-scaling agents and biocides in cooling towers may represent high environmental loads of hazardous substances. Although these are at relatively low concentrations, accumulation of chemicals can be harmful in the long term. A wide variety of processes are already employed in power plants to recover, recycle, and reuse water.

Cooling thermal power plants requires huge amounts of water.

Climate change will add to the risks of conflict between water and energy. The efficiency of the cooling process depends on the temperature difference between the cool and the hot waters. Consequently there are strict requirements on the temperature of water that is used. With a higher cooling water temperature more water is needed to provide the same cooling effect. Most plants have regulations or other constraints that limit their ability to adjust their withdrawal rates. In the short run this means that they will get less cooling, a corresponding decrease in turbine backpressure, less efficient generation, and less electric energy for the same amount of raw energy input. Also, many nuclear plants have safety limits on intake temperature that could trigger complete shutdowns more frequently in altered climate scenarios. In addition, environmental concerns usually impose limitations on the temperature of water discharged back into the streams and reservoirs.

Thermal power plants, agriculture, industrial and municipal users are competing for the same water resource. If a river's flow is reduced, as may happen seasonally, thermal power plants may find there isn't enough water available for cooling (see Section 13.1). This issue will only become more critical with climate change. It will be increasingly important to establish networks of water and energy professionals to deal with the close relationship between water and energy.

2.4 INDUSTRIAL POLLUTION

Due to many different pressures from agriculture, population growth, increasing urbanisation, and industrialization water quality has deteriorated, putting a major strain on water supply globally. Not only the level of water abstraction is reaching its natural limits but water quality deterioration has been driving scarcity and holds back economic growth in many developing countries. This calls for a dramatic shift in water utilisation concepts where water quality determines supply and how it can be most efficiently allocated.

In the world the industry uses some 22% of the freshwater (see Figure 6.1). In high-income countries the industry uses 59% of the water while in low-income countries industry uses only 10%. The annual water volume withdrawn by industry is estimated to rise from 750 km^3/year in 1995 to 1170 km^3/year in 2025, an increase of 55%.

Some 300–500 million tons of heavy metals, solvents, toxic sludge and other wastes accumulate each year from industry. Industries based on organic raw materials are the most significant contributors to the organic pollutant load with the food sector being the most important polluter. More than 80% of the world's hazardous waste is produced in industrial countries. In the developing countries some 70% of the industrial wastes are dumped untreated into waters where they will pollute usable water supplies.

Energy production, generation and use have a large water footprint and this includes both the consumption of water and contamination of the process water used for exploration or for refining the oil, gas, uranium or biomass. Another huge impact of energy production is the devastation caused by accidents, oil spills, leakages, broken dams for mining water and simply careless operations.

Industrial pollution of all kinds not only destroys water quality but will indirectly influence the available water supply resources. To make drinking water available from highly polluted water naturally requires more energy.

China and India can illustrate the serious consequences of poor water quality to water availability.

2.4.1 China

China announced in October 2011 (Water 21 Global News Digest, 18 October, 2011) to invest more than US$ 600 billion (10^9) over the next decade to overcome the severe water shortages that threaten the nation's growth. One of the reasons for the water shortage is the highly polluted waters. The vice minister of water resources, Jiao Yong, has said that the nation's swift economic growth has left up to 40% of its rivers badly polluted while the country also faces huge pressures on supplies.

Also the groundwater pollution is serious. As stated in Global Times, Beijing, 4 November, 2011: 'In the process of industrialized development, China is now facing the increasingly deteriorating quality of groundwater after so many years of soil infiltration by city sewage, household garbage, industrial wastes, fertilizers and pesticides.' On 28 October, 2011 the Chinese Ministries for Environmental Protection, Land Resources and Water Resources jointly released a National Plan on Groundwater Pollution Control for 2011–2020, the first for the country. A total of US$ 5.5 billion will be invested to fight the groundwater pollution. Water quality is classified in five classes. A survey of 641 wells in north-eastern and eastern China showed that only 26% of the wells met the Class 3 standard of drinking water. Classes 1–3 denote that the water is suitable for drinking. As much as 74% were classified as a Class 4 or 5. Class 4 water can be used as drinking water after undergoing treatment, and Class 5 is not suitable for drinking. North China is more affected by deteriorating groundwater quality because there are fewer rivers and lakes in the North.

The groundwater use in China has increased from 57 billion m^3 in the 1970s to 110 billion m^3 in 2009, accounting for 18% of the total water supply (Global Times, Beijing, 4 November, 2011). In 2010 it was reported to be 112 billion m^3 according to the National Groundwater Association (www.ngwa.org), see further Section 7.2. In the dry northern regions 65% of the domestic water, 50% of industrial water and 33% of agricultural water comes from groundwater. Also, more than 60% of 655 cities nationwide are using groundwater as a source for drinking water.

The Yangtze River receives annually about 40 million tons of industrial waste. Half of China's 20,000 petrochemical factories lie on its banks. Still the Yangtze River protection authority reassures that the quality of the river water is not degraded, since the river flow is so large, some 1 trillion (10^{12}) tons of water per year or some 32,000 m^3/second (Wuhan Evening News, 14 Nov 2011). Still other sources claim that this poses a threat to drinking water. About 40% of all wastewater produced in China – about 25 billion tons – flows into the Yangtze, of which only about 20% is treated before it enters the river system. The industrial pollution not only hits the main stream of Yangtze but many branches and lakes of the River. Their self-purification capacity is very limited. Monitoring of the wastewater is tightening.

2.4.2 India

The water situation in India is also serious. India has 17% of the world's population and only 4% of its fresh water resources. The water scarcity is caused by the population increase and the subsequent water demand but also of industrial growth. Groundwater is the major source of water and around 89–92% (depending on the source) of the groundwater is used in the agriculture, while 5–2% is used by industry and 3–9% by domestic users. The average decline the water table is 0.33 m per year. The industrial contamination is serious and there is a major concern about fluoride, arsenic and iron contamination. This is a challenge not only to the agricultural production and rural livelihoods, but also to the nation's food security.

Also most of the surface water is used for the agriculture, about 89%. The water quality is much affected by both point and non-point sources. Both agriculture and industry most often have an overuse of fertilizers and pesticides. Floods and droughts cause serious problems. The surface waters are dumping grounds for various offerings and on the boundaries of water bodies there is defecation which results in bacteriological contamination.

2.5 CHAPTER SUMMARY

- Increasingly water and energy resources are in conflict or in competition with each other, just another sign of the water-energy nexus.

- Huge water resources are needed for energy generation.
- The competition with agriculture increases. Food production is a major user of both water and energy resources.

2.6 MORE TO READ

Just-Netanyahu (1998) is a comprehensive book on conflicts and cooperation on transboundary water resources. The many issues in the book are still relevant. Both international (such as Middle East, Central Asia, the Euphrates and Tigris river basins) and domestic (within Australia, and US) cases are discussed.

De Villiers (2001) has produced a most readable book on water resources and their relationships to energy exploration and generation. Gleick (1993b) presents an excellent overview of conflicts related to water and energy. Gleick (2008) lists a chronology of water related conflicts from 3000 BC until recent times. He points out that water and water supply systems are increasingly likely to be both objectives of military actions and acts of war as human populations grow and as improving standards of living increase the demand for fresh water. He also outlines possible means to manage and mitigate the problems.

Baillat (2010) explores the fundamental question raised by international water transfer projects: to whom does water belong? The Colorado River is the topic of one of the case studies. The SIWI report Kim-Glaumann (2012) has a comprehensive list of transboundary water issues. Earle *et al.* (2010) and Zeitoun-Jägerskog (2011) have addressed transboundary water management. A key message is that failure to engage the basin hegemon constructively will hamper effective cooperation on transboundary waters.

Data from China have been found in local newspapers and personal communication with Yu Fanxian, Tsinghua University, Beijing. Economy (2004) presents a more comprehensive picture of the situation in China. Data from India is obtained from WHO, and Tania Datta, CH2MHill, Salt Lake City, USA.

3

The demand for holistic solutions

> *We can't solve problems by using the same kind of thinking we used when we created them.*
>
> Albert Einstein

Considering the close relationship between water and energy it is obvious that the challenges have to be treated in an integrated manner and single issues cannot be treated in isolation. The whole system has to be considered, including pure water resources, energy consumption, water usage, wastewater treatment, water reuse, receiving water and possible energy production. Integrated systems can only be considered by cooperation between several organizations (sometimes governments) and many different specialists. The interdisciplinary view has to be recognized, which also means that we have to exercise much more communication between engineers and scientists of different disciplines, but also between technology people and professionals in social sciences, behaviour sciences, economy and political decisions as well as between producers and consumers.

3.1 CONSEQUENCES OF THE WATER AND ENERGY NEXUS

A couple of examples may demonstrate how water and energy issues have to be considered together. Nothing else than integrated planning can resolve many of these challenges with unexpected couplings.

- *Hydropower obviously depends on water (Chapter 10).* The energy is renewable in the sense that water is all the time replaced with new water that will supply the turbines with new energy. However, the system is not without losses that can be significant in many places. Depending on the site the evaporation from the dam can be so significant that the power generating capacity can be severely constrained. It is obvious that the dam will influence the availability of water. In most cases it was designed to provide water, but in some cases it simply takes away the water for other purposes.
- *Oil and gas extraction depend on water (Chapter 11).* As the exploration of oil and gas is moving from conventional sources into shale gas or to oil sand the water need expands significantly. As the drilling is moving into deeper oceans the risks are growing and oil accidents become increasingly probable. When the oil exploration is moving from warm seas to the cold Arctic Sea the risks and consequences of accidents cannot be foreseen.
- *Coal mining operations have severe influence on water availability and water quality (Chapter 11).* This has devastating consequences for nature and people around the mining

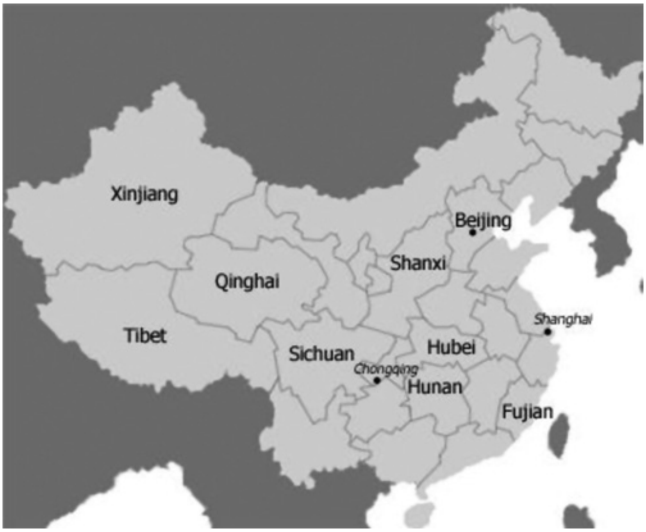
operations, and there are numerous examples from the US, China and from China. The competition with other water uses becomes manifested in many areas.

- *When biofuels are produced from corn or sugarcanes energy is apparently competing with food (Chapter 12).* Which is the best way to provide fuel for vehicles and save emissions: to provide biofuel or to make the engines more efficient?
- *Thermal power plants require cooling and water is the prominent medium because of its thermal properties (Chapter 13).* Climate change apparently influences not only temperature but also the availability of water. The cooling water may either be too warm or simply not available. The obvious consequence is that the operation has to be reduced or even shut down.
- *Water transport, treatment and distribution as well as wastewater collection and treatment require energy (Chapter 15).* Naturally all these operations can be made more efficient (Chapters 16, 17, 18, 19), in particular if plant wide or system wide operations are applied. Moreover, the consumer side should not be forgotten. In fact, in many high-income countries 90% of the energy related to the urban water cycle is used at home. Heating water takes a lot of energy.
- *Water scarcity is increasingly solved by desalination (Chapter 20).* The price is shown as energy requirement.
- *Our societies have been predominantly supply oriented, both in terms of energy and of water.* Climate change and water scarcity cannot be met without the engagement of all of us users on the demand side and both water and energy have to become more demand oriented (Chapter 21).

The interconnections between energy and water can also be shown in various ways, as illustrated by the power supply situation in China. Coal is still the main energy source for electric power (Chapter 11). The country has nearly half of the world's total coal-fired capacity. The coal price increased to record levels in 2011 due to the strong demand (International Herald Tribune, 25 May, 2011). This created a power struggle between the government planners and the utilities. The government tightly limits the prices they can charge the customers, while the power companies claim that they face financial ruin if they cannot raise the rates. The power companies are majority-owned by the government, but they are also profit motivated companies accountable to the other holders of their publicly traded stock. As a response the utilities were deliberately holding back the production and slowing down the construction of new plants. At the same time the electricity demand was rising.

In March 2011, responding to the power shortages, government officials in six provinces began rationing electricity. For example, in some places in the Hunan province (see Map 3.1), homes and businesses received power only every third day. Naturally this will influence the water availability. There was no running water on the days with no electric power, since the pumping stations were shut down. So, in many rural areas people had to go back to haul water from a well – as in the old times.

The low lying Pacific island state of Micronesia will be one of the victims of the climate change and the rising sea levels. Micronesia is a chain of more than 600 islands in the west Pacific and is already experiencing flooding and tidal surges as a result of rising sea levels. Much of Micronesia lies about 1 m above the sea level. Unless climate change is addressed, sea levels will rise by 1 m by the end of the century. Micronesia has mounted an unprecedented challenge against the Czech Republic's plans to expand a coal fired power plant Prunerov, more than 11,000 km away (Greenpeace, 2010). The reason is that Micronesia states that the potential environmental damage threatens the archipelago's survival. There is a fear of the increased greenhouse gas emissions and their contribution to the climate change. The power plant Prunerov II would be one of Europe's largest coal-fired power plants and the largest source of CO_2 emissions in the Czech Republic, 40 times more CO_2 than the population of Micronesia emits annually.



Map 3.1 Regions of China (selection).

The case has been supported by Greenpeace, which along with Micronesia, wants the Czech government to assess the effects of pollution from the power station on the archipelago. Such a transboundary environmental assessment is often requested by countries that share borders, but it has never been demanded by a nation in a different region and hemisphere. This is a new experience that energy and water issues are truly global.

The outcome of the challenge posed by Micronesia has not hindered the completion of the plant. However, the message is obvious: decisions made unilaterally by one nation that contribute to a rise in global CO_2 emission levels may be increasingly challenged by other countries. According to UNEP, Pacific island states have contributed just 0.06% to global GHG emissions, yet are experiencing the effects of climate change faster than most other nations in the world.

In a discussion with a colleague responsible for the water supply on one of the Pacific Islands he reminded me about the not so obvious threat. The rising sea level is an increasing risk for the low lying islands. Most of us, living far away from the threat, believe that this is a slowly growing hazard. My colleague opened my eyes: 'we are talking about the specific hour when our island will be wiped out of a wave'. The combination of a rising sea, warmer temperature and extreme events is disastrous. It is a problem created by us, the rich nations, but the price is paid by those far away. This is a deeply moral problem, related to climate change (Chapter 4).

3.2 INTEGRATED SOLUTIONS

The water and energy world seems to be split between those who believe that there are technical (engineering and scientific) solutions to the looming crisis in water and in energy respectively, and those who believe that the problem is more one of politics and management. I strongly believe that the solution will be a combination of improved technology, including better methods for water conservation and sustainable energy generation, and of political decisions and better management of the resources. This will include a more realistic pricing, but also systematic attempts to influence our attitudes and our behaviour.

Integrated solutions are necessary. Water and energy cannot be planned separately. Technical and non-technical issues have to be combined.

An integrated solution has to include both water and energy aspects. No longer can we divide the management of water supply and wastewater. Furthermore, the customers of the water and of the energy have to be considered together in the decision making. This implies that it is crucial to formulate adequate driving forces for the organisations and the people involved. It also includes ways to influence attitudes and habits.

Holistic solutions have to deal with a whole hierarchy of organizations and decisions. At the highest level we have to deal with intergovernmental management and agreement of common water resources. How to build dams in rivers that are shared by two or more nations? When to use water in shared rivers to minimize conflicts? Some examples were discussed in Chapter 2. For example, there is considerable skepticism in Central Asia about foreign involvement in resolving the water issue. Donors have favored technical rather than political solutions, and funds have been earmarked for the repair and replacement of inefficient irrigation installations. Technical solutions will only have a limited impact, however, if not accompanied by political measures.

Efficient water management requires quotas that are sustainable and are backed up by enforcement mechanisms and sanctions against violators. The policies have to be more transparent and accountable. The problems cannot be solved with only an engineering approach. Rather, multiple political, social and economic factors have to be considered. This is discussed for example for dam buildings in Chapter 10 or with biofuel in Chapter 12. This means that the mandate has to be broader than just water and energy.

It is my strong belief that an expanding funding for monitoring equipment, particularly automated systems would be needed. This cannot only provide transparent information but can also be an essential tool for early warning of disruptions, misuse, disturbances and accidental events. Local water user associations have to be supported as a way to introduce new technology, improve operation and reduce consumption and inefficiency.

Measurements, automatic monitoring and early warning systems are key technologies for water/energy operations.

On the river basin level there are a number of various interests in using the water. The power generation and the use of the river for cooling water for thermal power plants has to be planned in an integrated way to avoid conflicts with other water users.

On the individual plant level there are several considerations. A power plant can be planned for different kinds of cooling systems (Chapter 13). Thus, the requirement for water usage can be quite different. Likewise, a wastewater treatment plant and a drinking water supply system should be planned with energy efficiency taken into consideration from the design phase to the operational stage. This is further discussed in part Four.

3.2.1 System wide water operations

The energy issue is an apparent reason to consider integrated control in water and wastewater operations. In Olsson-Newell (1999), Chapter 14, we discussed the energy issue in water: '*The energy issue will be increasingly important in the future society. There is a significant indirect environmental impact due to the use of electrical power, heat and chemicals. Since energy production, transmission and distribution are related to environmental consequences, there will always be an incentive to save energy. Naturally, when comparing various systems for wastewater handling, the accumulated energy consumption of the total system has to be considered. This includes transportation of the wastewater, energy demand for treatment, the use of heat content in the water, and gas production. By looking at isolated subsystems from an energy point of view it is easy to obtain false solutions, and sub-optimisation has to be carefully avoided.*' The energy issue was, and still is, a major incentive why we have to consider plant-wide control and operation. We also wrote about the end user aspect: '*A lot of water – and warm water – is used to keep us clean and healthy. Only a minute fraction of the heat content of all this water is exploited, for example in heat pumps. If the heat content could be better utilised in cold climates in combination with the digester gas, then the wastewater treatment plants would be energy producers instead of consumers, for example to supply base heating in district heating systems.*' This is now a 'hot' issue indicated by conferences on Water and Energy. More is discussed in Chapter 14.

A waste treatment plant can be a net energy producer using a plant-wide approach and operation.

To maximize the efficiency means that we can no longer operate each unit process in isolation. Instead a plant-wide (system-wide) approach is in demand. The sludge production in the liquid train of an activated sludge system has to be related to the desired sludge level in the anaerobic digestion to produce biogas. The operation of the sewer has to relate to the capacity of the wastewater treatment system. The electrical energy consumption in the plant has to be minimized and this requires a plant-wide perspective. A wastewater treatment plant can serve as a net energy producer using the energy from biogas and effluent heat content. It is obvious that wastewater treatment plant operation is complex. What makes it increasingly complex is the mentioned requirements of efficient operation all around the clock. The plant has to consistently meet disturbances, making maximum use of available volumes, and all the time satisfying the requirement of the effluent quality.

Integration means a compromise. Each subprocess cannot be optimized in isolation.

All integration means some kind of compromise. If there were no interactions, then the individual optimisation of each subprocess would be the best strategy. In the system-wide operation of a wastewater treatment plant the individual system operations are sometimes in conflict, so the overall goal of minimising the load to the receiving water has to overrule the individual goals. Also for a drinking water plant the control has to be plant-wide so that high efficiency is obtained. All water that is produced has to meet the quality criteria. There is a tight coupling between the unit processes which forces the control to take the couplings into consideration.

3.3 WATER, ENERGY AND FOOD SECURITY

There is still no precise definition of *water security* but will be further discussed in Chapter 8. Hoffman (2004a) defines water security as '*the ability to access sufficient quantities of clean water to maintain minimal standards of food and goods production, sanitation and health*.'

> *When considering water and energy security we cannot neglect the influence of food security.*

The water and energy relationship to food will be further discussed in Chapter 6, but here we will illustrate some of the major couplings between them.

The major drivers to the water, food and energy securities are illustrated in Figure 3.1:

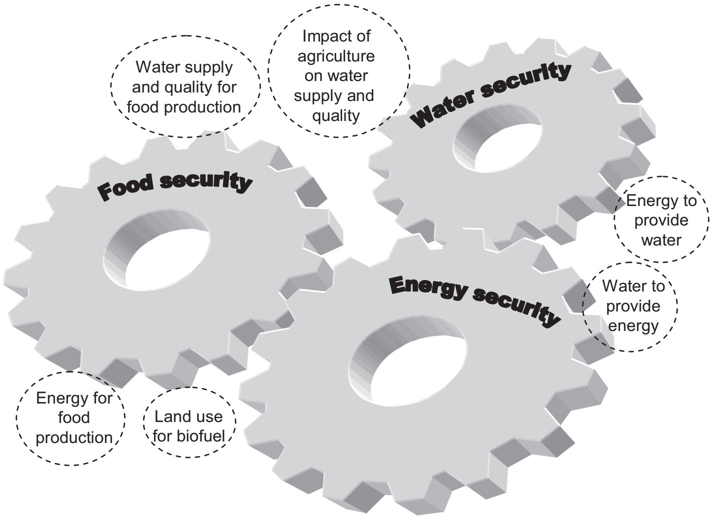


Figure 3.1 Water, energy and food securities are closely linked to each other. The only possible approach is an integrated resource planning.

- The **population increase** will put pressure on all the three types of security;
- The **growth of the economies** will increase the demand for both energy, water and food;

- The **urbanisation** will put a lot of demand not only on sanitation but also on drinking water, food availability and energy requirements;
- The **climate change** will influence all aspects of energy, water and food.

The environmental problems will certainly be huge considering the demands on both water and energy.

As Figure 3.1 illustrates the **water security** is influenced both by the energy and the food. Agriculture has a major influence on both water supply and on water quality. The water security depends on the available energy to provide the water. In particular in the developing world, the energy availability may be the real limiting factor for the water supply.

The **food security** depends on both water and energy. Water supply and quality are of course crucial for any food production, both plant and animal production. Also energy is crucial, both for food production and for transportation. The land has to be cultivated, which requires energy for machines (trucks and tractors), energy to mitigate land erosion and soil depletion. Then energy is needed to produce and deliver fertilizers and pesticides.

Energy security is getting increasingly connected to food security. As more land is being used for biofuel production there is a direct competition between food and energy. Water is a crucial ingredient in all energy production and electrical power generation. Water will become a limiting factor for energy generation in many places unless technology improvements or alternative energy sources are considered.

Two notions of security are often used, hard security (the ‘big S’ security) and soft security (the ‘little s’ security). With **hard security** we mean the security of physical infrastructures and the safety and reliability of them. Conflicts, war and social instability are reasons to pay particular interest on the hard security. For example, water and energy/power facilities are often considered targets of terrorist attacks. Taking hard security into consideration it is often attractive to diversify energy sources to make the system less vulnerable than having only few large units. The unequal distribution of water resources across regions or countries can create hard security concern, and in many places there is a growing talk of likelihood of ‘water wars’. The Middle East is probably the most apparent region where this is a reality.

Security considerations will of course make the physical protection of energy facilities important. For example, in March 2010 Venezuela arrested eight Columbians that were accused of espionage and sabotage against the nation’s electrical grid. The lack of energy can also undermine general security environment.

A couple of examples:

- *Senegal*: in July 2011 recurring electricity outages fuelled underlying discontent leading to anti government protests;
- *Venezuela*: in April 2010 drought forced prolonged electricity outages. President Chavez deployed Bicentennial Security Forces to Caracas to maintain order on the streets in light of growing public discontent. Reports and security forces used rubber bullets and tear gas to suppress protesters.

With **soft security** we mean human security, food security, economic development, sustainability and resiliency. Access to water is an important aspect of soft security. The lack of access to water was described in Chapter 1.2. This has a great impact on human security and economic development. Also we should consider:

> 1.6 billion lack access to reliable electricity;
> 1.4 billion lack access to modern fuel for cooking, lighting and heating;

> Nearly 1 billion people go to bed hungry.
> At the end of 2014 there were more than 6.9 billion mobile telephones and 2.3 billion mobile broadband subscriptions in the world (ITU statistics).

Ethiopia can be mentioned as one example: the cost of its inability to cope with drought/flood cycles corresponds to one third of its growth potential. This means that *water inequality is correlated with inequality.*

3.4 SUSTAINABILITY

Sustainability is a key word when we consider the future of water and energy. There are many ways to define it, but they all reflect a simple truth. We need to find new efficiencies by *doing more and using much less.*

This includes the development of new technologies and technical solutions and by using much less of water and energy. It also includes our lifestyle and consumption patterns.

Sustainability simply means doing more and using less.

Water is a very special commodity since it is finite. There will be no more water. When we talk about water use we have to be careful with the nomenclature. To spend water for a shower or a washing machine does not mean that the water is incapable of further use. Other 'uses' may leave the water unusable for anybody else, like in unconventional oil exploration. The control of the water is also lost when water evaporates from dams, cooling towers and fields or when it transpires in the photosynthetic process. This water cannot be returned to the system for possible reuse, at least not until nature will recycle the water.

3.4.1 Putting ecosystems into the planning

The World Conservation Union (IUCN) has stated that ecosystems should be counted as water infrastructures. This has many interesting consequences. Ecosystems have an economic value in relation to both water and energy, but this value is often poorly understood and rarely articulated (Emerton-Bos, 2004). Consequently it is often omitted in planning and decision making. Then these ecosystems lose their economic value as they are degraded and destroyed. This also leads to declining future profits, but the costs are often passed on to the end-users of the water products as higher fees or lower quality services.

The total economic value of ecosystems has four ingredients:

(i) Direct values, such as raw materials;
(ii) Indirect values, such as flood control;
(iii) Option values, which is the premium placed to maintain future development options and uses;
(iv) Existence values, such a tourism, spiritual values and so on.

All these values are important in the decision making. A quantification of the ecosystem benefits also allows comparison to other economic sectors and activities. We need to express ecosystem values as measures that make sense to decision makers. There will always be non-economic considerations in deciding between alternative projects. Multi-criteria analysis provides one tool to integrate various technical, ecological, economic and social criteria. This will be discussed specifically in connection with hydropower, Chapter 10.5, but is related to all energy exploration and generation.

3.5 FINDING EFFICIENT DRIVING FORCES

To dampen the water crisis everyone has to use less water. The threats of famine, pestilence and mass migration as a result of water scarcity are apparent. Wars will break out between countries that compete about the same water sources. Bringing supply and demand into equilibrium will require that every one of us share the task to reduce, that the political leaders take their responsibility and that the professional world will develop means to use the existing water supplies more wisely, and to clean up the polluted waters already there.

Water and energy pricing becomes a crucial tool to control the consumption and give incentives to become efficient in the water use and in the energy use. Too cheap energy and/or water contribute to inefficiency. There are too many examples of the misuse of either energy or water. Adequate pricing ought to be an efficient way to bring supply and consumption into balance.

We have to define driving forces both for the supply and for the demand side.

Too often the discussions on both energy and water have concentrated only on the *supply* side. This is of course important, but the *demand* side should not be neglected. Energy and water suppliers have the responsibility to inform and educate the users on efficient use of the resources. Furthermore, much of the current wastefulness is political in its origins. Both pricing and public policy are critical to any solution. It is still worth citing De Moor-Calamai (1997):

> ‘Aquifers are being drained, rivers are drying up, more than a billion people don’t have access to safe water, and vast tracts of irrigated land are being lost to salinity; over all, water is being lost in flood proportions and used inefficiently and for low-value purposes. And what are governments doing? Subsidizing this ecological vandalism, natural resource waste and economic perversity by selling water well below actual supply cost, much less than market value. The message of subsidy is clear: don’t worry about conservation or higher efficiency or recycling.’

Chapter 8 is devoted to the demand issues.

3.6 CHAPTER SUMMARY

- The water-energy nexus no longer is a local or regional issue but has global consequences. Integrated solutions are necessary.
- Population increase, the growth of economies, the urbanization and the overall threats of the climate change are key drivers.
- The water, energy and food securities are closely related. To obtain sustainable solutions we have to consider not only technical solutions but think in terms of reductions of all kinds of consumption. Efficient driving forces to save have to be found.

3.7 MORE TO READ

There are many reports available that give an overview of the water and energy problems and are directed to a broader audience. *National Geographic* has devoted several articles on water quality and water supply. In particular the special issues National Geographic (2010a, 2010b) ought to be mentioned.

The complex interrelations between water, food and energy are illustrated by four case studies from India, Ethiopia, Jordan and the US by McCornick *et al.* (2008) and by Hellegers *et al.* (2008). The UN WWDR (2014) report is a good introduction and the reports from FAO and the World Bank are very good sources of knowledge.

The web offers huge information and YouTube (www.youtube.com) has videos that can supply basic information on practically everything concerning water and energy: water and wastewater treatment, desalination, coal mining, oil exploration, hydropower, thermal power plants, and cooling systems.

PART II

Water vs. climate, population, energy, food and land use

In August 2011 Ecuador made a fundamental decision. The constitution was changed so that Nature has got similar rights as Humans (Ecuador constitution, 2011, Ch. 7). Nature is now a legal person or part.

In 1998 the South African government passed the National Water Act, which assures that ‘water is a natural resource that belongs to all people’. The law looks at river basins as ecological systems and requires that basic human needs, such as clean drinking water, and basic environmental needs, such as maintaining stream flows, are met before giving water to industry and agriculture. Still the national power generation is classed as ‘strategic use’, which means that the energy generation is guaranteed a supply of water and is authorized by the Minister. Electrical generation ‘is fundamental to the overall functioning of the country and the economy’ (National Water Act, 1998, p. 27ff). This clearly indicates a grave potential conflict in a water scarce country.

In the United States the Clean Water Act (CWA) was instituted in 1972. It establishes the basic structure for regulating discharges of pollutants into the waters of the US and regulating quality standards for surface waters. There are apparent conflicts between oil and gas exploration and the CWA, as explained in Chapter 11.

As expressed by the EU commission in a blueprint to Safeguard Europe’s Water Resources (EUR-Lex, 2012): ‘The Status of EU waters is not doing well enough!’ Further the document states: ‘The main causes of negative impacts on water status are interlinked. These include climate change; land use; economic activities such as energy production, industry, agriculture and tourism; urban development and demographic change. Pressure from these causes takes the form of pollutant emissions, water over-use (water stress), physical changes to water bodies and extreme events such as floods and droughts, which are set to increase unless action is taken. As a result, the ecological and chemical status of EU waters is threatened, more parts of the EU are at risk of water scarcity, and the water ecosystems – on whose services our societies depend – may become more vulnerable to extreme events. It is essential to address these challenges to preserve our resource base for life, nature and the economy and protect human health.’ European Water Policy has undergone a thorough restructuring process. A new Water Framework Directive was adopted in 2000. It is the operational tool and sets the objectives for water protection for the future (EU-WFD, 2014).

We will face major challenges due to the population increase and the resulting need for more food to the world. The demands from a growing population and the food that we need will have dramatic consequences for both the water resources and the energy use. Climate change is a consequence of our energy consumption, especially via fossil fuels. The changing climate will also have consequences for both the water resources and for the energy production and use.

4 Climate change

> *Det är ont om jordklot (Eng: There is a scarcity of Earth globes).*
> Swedish author and Nobel literature prize laureate
> Harry Martinson, from Gyro, 1947.

Water is the visible face of climate and consequently of climate change. Climate change has an impact upon the *average* volume of available water resources. It is manifested in increased water scarcity in some regions and flooding in other areas. More frequent extreme weather events – droughts (see Glossary), floods, heat waves or blizzards – are devastating to humans and the economy as they threaten and disrupt normal life in vast areas increasingly for longer periods. There are apparent couplings between climate change and energy production and consumption as well as between changing water availability and energy production.

Here we will use the terms 'climate change' and 'global warming'. The first term helps to convey the message that there are changes in addition to rising temperatures. In Section 4.1 climate change findings by the Intergovernmental Panel on Climate Change (IPCC) are summarized. The most apparent consequences of climate change are seen in new weather patterns and some of these phenomena are exemplified in 4.2. Energy production is causing climate change, but the reverse is also true. Both energy production and consumption will be significantly influenced by climate changes, Section 4.3. Many meetings have been held on the climate theme and some main results are summarized in 4.4 and some key actions are described in 4.5. The greenhouse effect is explained in 4.6 and the major greenhouse gases are described in 4.7. They have different influence on the global warming and their respective global warming potential is further discussed in 4.8. How can we mitigate climate change? The term frugality may characterize the necessary thinking, as discussed in 4.9. The chapter is summarized in 4.10.

4.1 GLOBAL WARMING

During the period 1901 – 2012 the global *average* temperature has increased 0.85°C (Anders Celsius, 1701–44, was a Swedish astronomer, physicist and mathematician. In 1742 he proposed the Celsius temperature scale which bears his name) and since 1950 the world has become 0.6°C warmer. In the Northern hemisphere it is likely to be the warmest period in 1400 years. The atmosphere and the oceans have warmed, the amounts of snow and ice have diminished, the sea level has risen, and the concentrations of greenhouse gases (GHG) in the atmosphere have increased (BAMS, 2014).

Monitoring the climate system at the global scale is an internationally coordinated enterprise. Since 1993, the World Meteorological Organization (WMO) has issued annual statements on the status of the global climate (www.wmo.int). The WMO Observing System acquires its information from over 10,000 surface weather stations, 1000 upper-air stations, over 7000 ships, over 1000 buoys, hundreds of weather radars and over 3000 specially equipped commercial aircraft that measure key parameters of the atmosphere, land and ocean surface every day. From the space operational polar-orbiting and geostationary satellites and also R&D environmental satellites complement ground-based global observations. Such a monitoring system is an example of extremely complex automation systems.

Climate system research involves many different disciplines, such as meteorology, oceanography, hydrology, biology, cryology (the study of snow and ice), and paleoclimatology (the science dealing with the climate of past ages). To determine the consequences of climate variability and change for the society requires many other disciplines, such as economics, sociology, history, political science, and urban planning,

The climate models are impressive examples of using ‘big data’ and are mathematical descriptions of the surface of the earth, the atmosphere, the sea, lakes and ice. In the models all of these are divided into a three-dimensional grid, and in every position of the grid temperature, moisture and wind are calculated. For the sea temperature, currents, salinity are computed. The global model grids are relatively sparse, with a size of 100–200 km, while regional models (e.g. for Europe) may have finer grids. In order to simulate the climate about 100 years into the future some 800,000 time steps are required. The global grid can contain some 2–3 million small cubes and all the data in each one of them is recalculated in every time step. In the last climate modelling project research groups from the entire world provided hundred times more data than in the last project 4–5 years earlier. The resolution of the models has increased from grid sizes of 500 km in the IPCC FAR model from 1990, 250 km in the SAR model from 1996, 180 km in the TAR model from 2001 to 110 km in the AR4 model in 2007. The vertical resolution has increased so that the models include 30 levels of the atmosphere and 30 levels of the sea.

The last decade has been the warmest. For the longest period when calculation of regional trends is sufficiently complete (1901 to 2012), almost the entire globe has experienced surface warming.

The last three decades have been successively warmer than any decade since 1850.

June 2014 marked the 38th consecutive June and 352nd consecutive month with a global temperature above the 20th century average. The last below-average global temperature for June was June 1976 and the last below-average global temperature for any month was February 1985 (NOAA, 2014).

Until 2100 global warming is assumed to increase between 0.9 and 6.0°C, compared to the late 19th century, depending on global emissions. The temperature increase over land and over the arctic regions will be even larger.

4.1.1 Intergovernmental panel on climate change – IPCC

Much of our knowledge on global warming has been compiled by the Intergovernmental Panel on Climate Change (IPCC), founded by WMO and UNEP (United Nations Environment Programme) in 1988. The panel comprises 195 countries and a large number of organizations. Around every five years IPCC has published a scientific summary of climate change, its consequences and possibilities to mitigate the consequences of climate change. This is the most comprehensive information source on the greenhouse effect and possible consequences of climate change. The IPCC does not undertake independent scientific research. Rather it compiles all key research published in the world and produces a consensus. This means that a huge number of scientific reports have been examined and the results *where all the parties can agree* have been accepted for the IPCC reports.

The assessment reports (IPCC, 2001, 2007, 2013, 2014a, 2014b) have been important sources for this chapter. The fifth assessment (AR) report, called AR5, has been published in 2013–2014, where over 800 scientists from 85 countries have contributed. It provides the view of the current state of scientific knowledge relevant to climate change. The AR5 consists of three Working Group (WG) reports and one Synthesis Report which integrates and synthesizes material in the WG reports for policymakers:

- *WG 1* – the physical science basis (IPCC, 2013) contains 1552 pages of observations and evidence, including 9200 citations of scientific papers. The final meeting was held in Stockholm in September 2013 (See Chapter 4.4) where the report was released. The Summary for Policymakers was approved line-by-line and accepted by the Panel of 195 member Governments.
- *WG 2* – impacts, adaptation and vulnerability. This WG considered the vulnerability and exposure of human and natural systems, the observed impacts and future risks of climate change, and the potential for and limits to adaptation. The report cites 12,000 scientific references. The summary for policy makers (IPCC, 2014a) was approved line by line and accepted by a Panel from the 195 countries, at a meeting in Yokohama, Japan, in March 2014.
- *WG 3* – assesses the mitigation (meaning ‘to make something bad less severe’) of climate change (IPCC, 2014b). The final meeting was held in Germany in April 2014. The report analyses around 1200 scenarios generated by 31 modelling teams from around the world to explore the economic, technological and institutional prerequisites and implications of mitigation pathways, looking at various degrees of mitigation.
- The Synthesis Report draws on the assessments made by all three Working Groups and has been published on November 1, 2014 (IPCC, 2014c). It provides an integrated view of climate change as the final part of the AR5.

The AR5 has further verified many of the serious consequences of climate change. The number of scientific publications available for assessing climate-change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation (the process of adjustment to actual or expected climate and its effects). The degree of certainty in key findings in this assessment is based on the author teams’ evaluations of underlying scientific understanding and is expressed as a *qualitative level of confidence* (using the five qualifiers *very low, low, medium, high*, and *very high*). There may also be other climate related results published in peer review scientific journals, but have results that a majority of the panel members were not ready to accept. In the following text we use the IPCC terminology summarized in Table 4.1.

From a water point of view the AR5 has found that climate change due to unabated greenhouse gas emissions within this century is *likely* to put 40% more people at risk of absolute water scarcity than would be the case without climate change. A key finding of the AR5 by the WG 1 is (IPCC, 2013, Sections 10.3–10.6, 10.9): ‘It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century.

The evidence for human influence has grown since AR4 (IPCC, 2007)'. This conclusion is extremely solid scientifically and comes from many independent sources of evidence. Natural factors like solar variability and volcanoes may have caused a certain warming or cooling influence recently, but they are on top of the human contribution and small by comparison.

Table 4.1 IPCC terminology.

IPCC expression	Meaning
Virtually certain	99–100% probability
Extremely likely	95–100% probability
Very likely	90–100% probability
Likely	66–100% probability

> IPCC: 'It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. The evidence for human influence has grown since 2007.'

As IPCC remarks: it is important to look at longer data series when the global mean temperature is monitored. Due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. For example, the rate of warming during the period 1998–2012 is only 0.05°C per decade. An important reason is that the period started with a strong El Niño (see 'Ocean' section below), making the trend smaller than the rate calculated for the whole period 1951–2012, which is 0.12°C per decade (IPCC, 2013, Section 2.4).

4.1.2 Other works to address climate change

The United Nations Framework Convention on Climate Change (UNFCCC, 2014) is the main multilateral forum focused on addressing climate change, with nearly universal participation. The UNFCCC was opened for signature in 1992. The Framework Convention entered into force in 1994. As of March 2014, UNFCCC has 196 parties. The parties to the convention have met annually from 1995 in Conferences of the Parties (COP) to assess progress in dealing with climate change. In 1997, the Kyoto Protocol was concluded and established legally binding obligations for high-income countries to reduce their greenhouse gas emissions. Some other COP meetings are discussed below.

The World Bank provides significant financing to mitigate climate change (www.worldbank.org/en/topic/climatefinance). In 2013 the World Bank Group provided US$ 6.5 billion in lending for mitigation efforts and US$ 2.9 billion for adaptation. In particular, the poorest countries got a mitigation support of US$ 2.3 billion via the International Development Association (IDA) in 2013, while adaptation support was US$ 2.1 billion. The private sector arm of the World Bank, the International Finance Corporation (IFC) has invested US$ 2.5 billion in 2013 in renewable energy and energy efficiency, a 50% increase over 2012. The World Bank estimates that the developing (I prefer to use the term *low-income*) countries will require US$ 75–100 billion per year over the next 40 years to build resilience to climate changes. Mitigation costs are expected to be in the range of US$140–175 billion per year by

2030. According to the International Energy Agency (IEA) the world needs US$ 1000 billion per year between 2012 and 2050 to finance a low-emissions transition (Buchner *et al.* 2012).

Climate change, established as increases in temperature, changes in precipitation and decreases in ice and snow has been recorded specifically for Europe by EEA (2012). Compared to the preindustrial level the mean temperature and the frequency and length of heat waves have increased across Europe. In the last decade before 2012 the average temperature over land in Europe was 1.3°C warmer than the preindustrial level, which makes it the warmest decade on record. Over the same period precipitation increased in Northern and North Western Europe but decreased in Southern Europe. Observations regarding storms show no clear trend. Storm frequency increased from the 1960s to 1990s, but was followed by a decrease to the present. According to EEA, several indicators now include projections of further snow and ice decline. If greenhouse gases continue to be emitted at high levels, EEA predicts that the Arctic Ocean will be nearly ice free every September before the middle of the century.

US National Climate Assessment (NCA, 2014) is probably the most comprehensive report on the impacts of climate change in the US produced to date. The NCA documents observed and projected climate impacts across regions and economics sectors in the US. The report notices that climate change, once considered an issue for a distant future, has moved firmly into the present. Summers are longer and hotter, and extended periods of unusual heat last longer than any living American has ever experienced. Winters are generally shorter and warmer. Rain comes in heavier downpours. Residents of some coastal cities see their streets flood more regularly during storms and high tides. Inland cities near large rivers also experience more flooding, especially in the Midwest and North East. In Arctic Alaska, the summer sea ice that once protected the coasts has receded, and autumn storms now cause more erosion, threatening many communities with relocation. Climate researchers confirm that these observations are consistent with significant changes in the Earth's climatic trends.

The US average temperature has increased in between 0.7°C (1.3°F) and 1.1°C (1.9°F) since record keeping began in 1895. Most of the increase has occurred since 1970. The force, frequency and duration of North Atlantic hurricanes, as well as the frequency of the strongest hurricanes, have all increased since the early 1980s.

Global warming continues. According to the US NOAA (NOAA, 2014) and the Japan Meteorological Agency's Tokyo Climate Center the globally averaged temperature over land and ocean surfaces was the highest for the month of June 2014 since record keeping began in 1880. This follows on the highest ever temperature measured for the month of May. Furthermore, June 2014 was the 3rd month in a row when the average CO_2 levels exceeded 400 ppm.

4.1.3 The oceans

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*). Over 60% of the net energy increase in the climate system is stored in the upper ocean (0–700 m) and about 30% is stored in the ocean below 700 m (IPCC, 2013, Ch. 3.2).

According to the Goddard Institute for Space Studies (GISS) the record temperature in 2010 (http://earthobservatory.nasa.gov/IOTD/view.php?id = 48141) is particularly noteworthy, because the last half of the year was marked by a transition to strong La Niña conditions. La Niña is the 'gift giver', bringing cold, nutrient-rich water to the equatorial Pacific off South America. Those nutrients are a boon to marine life, supporting a larger fish population and increasing the fishermen's catch. The La Niña in 2010 was one of the strongest La Niña events in the past 50 years, according to GISS. Climatic impacts include heavy rains and flooding, which has damaged crops and flooded mines in Australia and Asia. It also has resulted in flooding in Northern South America and drought conditions in Argentina. 'This powerful little lady is spreading her curses and blessings across the planet. She's the real deal.'

The counterpart of La Niña is El Niño (Spanish for 'the boy child'). Peruvian fishermen named the climate phenomenon after the Christ child because it usually shows up around Christmas time. With the El Niño phenomenon surface temperatures in the tropical Eastern Pacific periodically warm up. IPCC finds that the El Niño-Southern Oscillation (ENSO) will remain the dominant mode of inter-annual variability in the tropical Pacific, with global effects in the 21st century (IPCC, 2013. Ch. 5.4, 14.4). Due to the increase in moisture availability, ENSO-related precipitation variability on regional scales will *likely* intensify.

The global mean sea level is rising. Since the early 1970s, glacier mass loss and ocean thermal expansion from warming together explain about 75% of the observed sea level rise (*high confidence*). Over the period 1993 to 2010, global mean sea level rise is, with *high confidence*, consistent with the sum of the observed contributions from ocean thermal expansion due to warming, from melting glaciers, the Greenland ice sheet, and the Antarctic ice sheet, as well as land water storage. These contributions add up to 2.8 mm/year. The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation (IPCC, 2013, Ch. 11–13).

In South East Asia, coastal cities will be under intense stress due to climate change (World Bank, 2013). A sea-level rise of 300 mm, possible by 2040 if 'business as usual' continues, this could:

- cause massive flooding in cities and inundate low-lying cropland with saltwater corrosive to crops;
- result in the loss of more than 10% of crop production in Vietnam's Mekong Delta, a global rice producer.

At the same time, storm intensity is *likely* to increase. The study also describes rising ocean acidity, leading to the loss of coral reefs and the benefits they provide as fish habitats, protection against storms and revenue-generators through tourism. Warmer water temperatures and habitat destruction could also lead to a 50% decrease in the ocean fish catch in the southern Philippines.

Storm intensity is likely to increase.

The Asian Development Bank (ADB) reports that East Asia is very vulnerable to the impacts of sea-level rise in both exposed population and assets. Japan and China are highly vulnerable to the impacts of sea-level rise. Three cities in East Asia – Guangzhou and Shanghai in China and Osaka/Kobe in Japan – are in the top 10 in the world in terms of current exposed population. In terms of value of assets exposed, three Japanese cities are in the top 10: Nagoya, Osaka/Kobe, and Tokyo. A significant portion of the population in both Japan (24%) and in China (11%) live in a low-elevation coastal zone (LECZ, below 10 meters elevation) (ADB, 2013a, p. 42). The ADB report notes that while climate adaptation investments can be large, the aggregate cost to protect the most vulnerable sectors – infrastructure, coastal protection, and agriculture – would be less than 0.3% of East Asia's GDP annually between 2010 and 2050.

4.1.4 Arctic areas and Antarctica

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic Sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (***high confidence*** according to IPCC, 2013, Ch. 4.2–4.7).

The Arctic Sea ice is melting drastically, opening the sea to shipping and the seafloor to mineral exploration. The *annual mean* Arctic Sea ice extent has been reduced by 3.5–4.1% per decade (450,000–510,000 km^2 or the equivalent area of one Sweden or Spain per decade) during the last 30 years. The reduction during this period seems to be unique for the last 1450 years. IPCC further claims that it is *very likely* that the *summer sea ice minimum* (perennial sea ice) will be reduced in the range 730,000 to 1,070,000 km^2 per decade. It is *very probable* that this is caused by human activities. The Arctic Sea can be free from ice during the summers before 2050 if the emissions continue to be large. Even if the emissions are small the ice in the Arctic will be significantly reduced all year round (IPCC, 2013, Ch. 4.2, 5.5).

Already ships have passed both the North West passage north of Canada and the North East passage north of Siberia. These new shipping routes may reshape the global transport system but will also affect national security interests in Russia, US and Canada. These developments are potential sources of competition and conflict for access and natural resources. The floor of the Arctic Ocean appears to be rich in petroleum. According to US Geological Survey 13% of the undiscovered oil reserves and 30% of undiscovered natural gas are assumed to be located north of the Arctic Circle. The seafloor is being eyed by the five countries bordering it: Canada, Denmark (which governs Greenland), Norway, Russia and the US. All have ambitions to claim a piece. So, climate change will create opportunities to burn more fossil fuel and to increase CO_2 and mean sea level further. The environmental risks for oil exploration under the cold sea are apparent. Oil exploration is already causing huge water damages, as discussed more in Chapter 11.

In 2013 Arctic environment ministers from Canada, Russia, the US, Denmark, Finland, Iceland, Norway and Sweden called for urgent action to reduce black carbon, methane and hydrofluorocarbons, to protect the Arctic and reduce the risk of triggering self-amplifying feedback mechanisms that lead to irreversible climate impacts. The call to action was presented at the conclusion of a two-day meeting in Sweden of the Arctic Council, a high-level intergovernmental forum (www.arctic-council.org). However, so far the Arctic Council has been unable to protect the Arctic Sea from oil exploration. The Russian oil giant Gazprom tried to start commercial oil exploration in the Arctic in 2013. At one event in September 2013 30 activists and freelance journalists on the ship Arctic Sunrise protested. They were imprisoned in Russia for about three months, accused of piracy (www.greenpeace.org/international/en/campaigns/climate-change/arctic-impacts). See further Section 11.5.

The melting of the Greenland ice sheet has been accelerating since the 1990s. Exceptional melting was recorded in the summer of 2012. The average rate of (net) ice loss from the Greenland ice sheet has *very likely*substantially increased from 34 Gt/year (1 gigaton = 10^9 tons) over the period 1992 to 2001 to 215 Gt/year over the period 2002 to 2011 (IPCC, 2013, Ch. 4.4). 100 Gt/year of ice loss is equivalent to about 0.28 mm/year of global mean sea level rise. Also the Antarctic ice sheet has been reduced. The average rate of (net) ice loss from the Antarctic ice sheet has *likely* increased from 30 Gt/year over the period 1992–2001 to 147 Gt/year over the period 2002 to 2011 (IPCC, 2013, Ch. 4.4). 147 Gt corresponds to an ice sheet with the thickness of 0.3 m covering France – every year. 215 Gt is 46% more, so the virtual ice sheet would be 0.44 m thick.

There is *high confidence* that permafrost temperatures (see Glossary) have increased in most regions since the early 1980s (IPCC, 2013, Ch. 4.7). In parts of Northern Alaska observed warming was up to 3°C (early 1980s to mid-2000s) and up to 2°C in parts of the Russian European North (1971 to 2010). In the latter region, a considerable reduction in permafrost thickness and areal extent has been observed over the period 1975 to 2005. As a consequence more methane will be released to the atmosphere, further exacerbating global warming. This is, for example, noted at the research station Zackenberg on North Eastern Greenland. Every year the permafrost will drop 10 mm.

There is *very high confidence* that the extent of Northern Hemisphere snow cover has decreased since the mid-20th century (IPCC, 2013, Ch. 4). Northern Hemisphere snow cover extent decreased at an average 1.6% per decade for March and April, and 12% per decade for June, over the 1967 to 2012 period. In the Northern Hemisphere during this period snow cover extent did not show a statistically significant increase in any month. For the hydropower this already has consequences (see Chapter 10), since the storage of water will be distributed differently during the annual cycle.

The shrinking of Andean glaciers has also been well documented. They have shrunk between 30% and 50% since the 1970s. Worst affected have been the smaller, lower altitude glaciers that supply potable water for much of the continent, the IPCC document warns. It adds that future climate change could completely destroy these lower altitude glaciers (IPCC, 2013. Ch. 4).

4.1.5 Signs in nature

The natural environment notes that the world is becoming warmer. When the temperature rises, the living conditions of animals and plants change and many species cannot relocate. In my own country Sweden the northern limit for agriculture moves towards the north with a rate of about 10 km per year, or around 1 meter per hour (Björklund *et al.* 2008). This looks like a moderate speed for humans but is a huge speed for many plants and eco systems. In northern and relatively cold regions it is now possible to grow plants that did not grow before because of the cold temperature. But it also means that new noxious insects and other animals as well as weeds will move. More information on the maximum speed which species can move is found in IPCC (2014a, p. 15).

When the sea absorbs more carbon dioxide it becomes more acidic, which seriously affects coral reefs and other calcium-dependent organisms. The number of species is already decreasing at a fast rate. This trend will accelerate (IPCC, 2014a).

4.1.6 Impact on water resources

Both IPCC and EEA analyze the climate impact on water resources (IPCC, 2013, Ch. 12.4, 14.3; EEA, 2012). Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions. EEA (2012) explains some of the consequences: a decrease in river flows in Southern and Eastern Europe (particularly in summer) and an increase in other regions (particularly in winter); increases in the reported number of flood events (mainly due to land-use changes and better reporting); increase in the frequency and intensity of droughts (particularly in Southern Europe); increase in water temperature in rivers and lakes; northwards migration of warm and cold-water species.

Some rivers will run dry in Europe as well as on other continents. Europe has been affected by several major droughts in recent decades, such as the catastrophic drought associated with the 2003 summer heat wave in central parts of the continent and the 2005 drought in the Iberian Peninsula. As a result of the heat wave in 2003 reservoirs and rivers used for public water supply and hydro-electric schemes either dried up or ran extremely low. Forest fires broke out in many countries. In Portugal 215,000 hectares area of forest were destroyed. It is estimated that millions of tonnes of topsoil were eroded in the year after the fires as the protection of the forest cover was removed. This made river water quality poor when the ash and soil washed into rivers. Food production was severely affected: many chickens, pigs and cows died during the heat in Europe and crops failed in the dry conditions. This led to higher food prices. Public water supply shortages occurred in several countries. Severity and frequency of droughts appear to have increased in parts of Europe, in particular in Southern Europe. Regions most prone to an increase in drought hazard are South and South Eastern Europe, but minimum river flows are also projected to decrease significantly in many other parts of the continent, especially in summer.

The World Resources Institute Aqueduct project (WRI, 2013) evaluated, mapped and scored water risks in 100 river basins, ranked by area and population, and 180 nations. WRI found that 36 countries face ‘extremely high’ levels of water stress, indicating that more than 80% of the water available to agricultural, domestic, and industrial users is withdrawn annually – leaving businesses, farms, and communities vulnerable to scarcity.

4.2 CLIMATE CHANGE IMPACT ON WEATHER

Changes in extreme weather events are the primary way that most people experience climate change. Mankind can live, survive and even flourish in extreme climates, from Siberia to Sahara. The problems arise when the expected extremes of local climate are exceeded. Droughts and floods, heat waves and storms in one region may be considered close to normal in another. This is because each region and society has a ‘coping range’, a range of weather that it can handle. When the climate is moving slowly to a higher temperature average and the coping range stays the same, then there will be more extremes. For example, in the historically mild climate of continental Europe homes have been built with central heating but no air conditioning. As summer temperatures increase and heat waves like the 2003 European heat wave (maximum temperatures of 35 to 40°C were repeatedly recorded and peak temperatures climbed well above 40°C; IPCC, 2007, Ch. 12.6.1) become more common, then the coping range of the homes will be exceeded and the houses would need air conditioning. Expressed differently, one of the great challenges of global warming is to start to build as much as possible with flexibility and resilience in the coping ranges in the society. A high-income country can do this, but the poorest populations cannot afford it. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development.

The coping range of a society has to increase to meet global warming.

4.2.1 Risks of extreme events and disasters

IPCC has produced a Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC SREX, 2012). This is an important source of information on changing weather and climate extremes. According to IPCC (2013, Ch. 2 & 6, Table SPM.1) changes in many extreme weather and climate events have been observed since about 1950. IPCC reports that 13 of the 14 warmest years on record have occurred in the 21st century. The global warming trend continues with floods, droughts and extreme weather events around the world. As expressed in 2013 by the WMO secretary-general Michel Jarraud: 'The growing impact of weather extremes cannot be ignored. Over the last 30 years natural disasters took the lives of over two million people and produced economic losses estimated at over 1.5 trillion (10^{12}) dollars.' The World Bank has issued a report on the Middle East and North Africa (MENA) region (World Bank, 2014). It states that the absolute numbers of disasters around the world has doubled since the 1980s while the number of natural disasters in the MENA region has almost tripled in the same period. IPCC reports a substantial progress in the assessment of extreme weather and climate events since AR4 (IPCC, 2013, Ch. 9.3). Simulated global-mean trends in the frequency of extreme warm and cold days and nights (see the Glossary) over the second half of the 20th century are generally consistent with observations. There has been further strengthening of the evidence for human influence on temperature extremes since the IPCC SREX (2012 report), according to IPCC (2013, Ch. 10.6). It is now *very likely* that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century. It is *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations.

> *It is now very likely that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century.*

Recent results from a group of researchers at the Potsdam Institute for Climate Impact Research in Germany (Coumou *et al.* 2014) focuses on the contortions in the narrow current of high winds across the Northern Hemisphere known as the jet stream as it flows around the northern mid-latitude. Large north-to-south bends in the jet stream winds, known as Rossby waves, can lead to strong high and low pressure areas that are difficult to dislodge. The study found a statistically significant increase in the frequency of certain Rossby waves since the year 2000. Rapid Arctic warming since 2000 may be reshaping and rerouting the jet stream, forcing it to act like a giant stop light at 10,000 m. This leads to stalled and prolonged weather systems that can bring deadly extreme heat and rainfall events. The study is part of a wave of research focused on the potential ties between melting sea ice and skyrocketing air temperatures throughout the Arctic, and extreme weather events in the northern mid-latitudes, including the US, Europe and Asia. The report adds to growing evidence that manmade global warming may already be reshaping today's weather patterns in ways that favor dangerous storms.

Worse is yet to come, the IPCC scientists have concluded (IPCC, 2014a). The report warns that the world's food supply is at considerable risk because of reduced water availability, and also predicts the risk of death or injury in low-lying coastal zones and on small islands, due to storm surges, coastal flooding and sea level rise (see above 'The Oceans'). There will *likely* be damage to public health, displacements and potential mass migrations.

4.2.2 Economic losses related to weather

The last decade has seen an exceptional number of extreme heat waves around the world with consequential severe impacts (World Bank, 2012; WMO, 2011). Human-induced climate change since the 1960s has increased the frequency and intensity of heat waves and thus also *likely* exacerbated their societal impacts. In some climatic regions, extreme precipitation and drought have increased in intensity and/or frequency with a *likely* human influence.

From the ten most commonly reported disasters, nine are directly or indirectly related to weather and climate (World Meteorological Organization, www.wmo.int). Vulnerability to disasters is increasing as more people and assets locate in areas of high risk. Since 1970, the world's population has grown by 87%. During the same period, the proportion of people living in flood-prone river basin increased by 114% and cyclone-exposed coastlines by 192%. Rapid urbanization and the growth of megacities will increase exposure to natural hazards. According to WMO, climate change is expected to increase the frequency and intensity of the most severe weather related hazards in the decades to come.

> *Climate change is expected to increase the frequency and intensity of the most severe weather related hazards in coming decades.*

Over the last five decades, economic losses related to hydro-meteorological hazards have increased, from around US$ 10 billion (10^9) in the decade 1956–65 to some 500 billion in the 1996–2005 decade. In the same period the human toll has fallen dramatically, thanks to scientific advances in forecasting and early warning systems combined with pro-active disaster risk reduction policies and tools. In the decade 1956–65 there were some 2.9 million casualties from hydro-meteorological hazards and in 1996–2005 the number had decreased to around 0.2 million (www.wmo.int).

The insurance industry has in recent years incurred major losses as a result of extreme weather. 2011 is regarded as a record year for natural catastrophes, with insured losses costing the industry over US$127 billion (Lloyd, 2014). A series of catastrophes at the end of the 1980s and the beginning of the 1990s posed a major challenge to the insurance industry. Natural catastrophe models were being further developed in the 1990s to help the industry to analyse and measure risk more accurately. Given the prevalence of catastrophe models in insurance and the rising cost of extreme weather events, the accuracy of modelled outputs is a key interest for insurers. Catastrophe modelling technology is now used extensively by insurers, reinsurers, governments, capital markets and other financial entities. Given the heavy use of historical data it is natural that climate change trends may be implicitly built into catastrophe models. There are naturally uncertainties associated with the estimation of the extent and frequency of the most extreme events. As a result climate change impact can be difficult to account for in risk models. There is a relationship between sea surface temperatures, sea level rise and hurricane strength which suggests a gradual increasing trend. This was analyzed specifically for the Superstorm Sandy in 2012 (see below). The sea-level rise at the southern tip of Manhattan Island was around 0.2 m. This increased Sandy's surge losses by 30% in New York alone. Further increases in sea-level in this region may non-linearly increase the loss potential from similar storms. Lloyd (2014) concludes that future climate scenarios could see increases in the frequency of intense storms in Europe, with a possible shift in storm track towards northern latitudes. It also notes that climate change has already increased the probability of flood events in the UK, and 1-in-5 rainfall event could be 40% larger in the future.

4.2.3 Extreme weather events

Simulated global-mean trends in the frequency of extreme warm and cold days and nights over the second half of the 20th century are generally consistent with observations. Still the report about different weather extremes (IPCC, 2014a) is similar to the report from 7 years earlier.

IPCC (2013, Ch. B.1) concludes that it is *very likely* that on the global scale

- the number of cold days and nights (see Glossary) have decreased;
- the number of warm days and nights (see Glossary) have increased.

It is *likely* that

- the frequency of heat waves have increased in large parts of Europe, Asia, North America and Australia;
- there are more land regions where the number of heavy precipitation events have increased than where it has decreased;
- the frequency or intensity of heavy precipitation events have increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most *medium*.

It is *likely* (IPCC, 2013, Table SPM.1) that

- human influence has more than doubled the probability of occurrence of some observed heat waves in some locations;
- the frequency and intensity of drought has increased in the Mediterranean and West Africa, and decreased in Central North America and North West Australia.

In the *absence* of climate change, extreme heat waves in Europe, Russia, and the United States, for example, would be expected to occur only once every several hundred years. Observations indicate a *tenfold increase* in the surface area of the planet experiencing extreme heat since the 1950s (World Bank, 2012). According to the UN climate scientists within IPCC, South Europe will be gripped by fierce heat waves, drought in North Africa will be more common, and small island states face ruinous storm surges from rising seas. The panel also notes that cyclones, heat waves, torrential rains, and drought will hit the world unevenly. The Eastern and Southern United States and the Caribbean will probably face hurricanes amplified by heavier rainfall and increased wind speeds. Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent by the end of this century, as global mean surface temperature increases.

We learn about drought and flooding, and also about what happens when you can no longer rely on the rains coming, when diseases spread or salt water contaminates wells. As is so often the case, those who live in poverty are affected first. Shifting rain patterns flood some regions and dry up others as nature demonstrates a grave physics lesson: hot air holds more water molecules than cold. Some examples from the last few years:

- The **oceans** have slowly become warmer. Probably this is the most important reason why tropical cyclones have been stronger than usual during recent years.
- Large parts of **Africa** have become dryer. In particular the Sahel, south of Sahara, has been hard hit during the last decades. When the evaporation increases the already dry soil will become drier.

- ***Pakistan***, *2010–2012*: The flooding in Pakistan in July 2010 was an extended catastrophe and UN representatives reported that they had never seen a more serious flooding, which left 1/5 of the country submerged by water, according to the National Disaster Management Authority. Heavy rainfall, flash floods and riverine floods in combination created a moving body of water equal in dimension to the land mass of UK. These floods wreaked more havoc than any other natural disaster the area had seen. The floods lasted for weeks, affecting more than 20 million people. Much of the land inundated in 2010 was in the Punjab province, Pakistan's breadbasket. Many in the country were barely recovering when unprecedented monsoon rains caused flooding from early August 2012 onward of the Indus river, spreading south through Punjab, Balochistan and Sindh. Still in early October 5 million people were affected by flooding.
- ***Russia***, *2010*: The heat wave and the dry summer caused enormous economic losses, both from failed harvests and from all the fires. It gave Russia the worst drought conditions in roughly 40 years. Around 90,000 km^2 of crop perished. Not only did the crops perish but the desiccated crop remnants were prone to catching fire (www.metoffice.gov.uk). Estimates for the 2010 heat wave in Russia put the death toll at 55,000, annual crop failure at about 25%, burned areas at over 10,000 km^2, and economic losses at about US$15 billion (1% of the gross domestic product) (www.bloomberg.com; Wikipedia).
- ***Philippines***, *2010*: In October the typhoon Megi – the 13th in 2010 – hit the Philippines and later the Fujian region in South East China (see Map 3.1), the worst typhoon in 20 years. In South East Asia it caused serious floods and Vietnam had the worst flood damages in 60 years.
- The year **2011** started with several extreme weather events, such as unusually heavy rains causing inundations in Queensland, Australia, and in Sri Lanka. The flooding in Thailand in 2011 caused enormous damage. Torrential rains in Brazil resulted in serious landslides in the mountain areas north and northwest of Rio de Janeiro.
- ***China*** *2011–2013*: In China there has been a combination of heavy rains and an increasing rate of glacier melting in the Himalayas. This increases the risks for flooding during the rainy season. At the same time the dry periods seem to be drier. China has long been affected by desertification in the northern and western regions. In 2011 parts of China suffered their worst drought in 50 years, with rainfall 40–60% less than normal, damaging crops and cutting power from hydroelectric dams. In April 2012 a devastating drought in South Western China's Sichuan and Yunnan provinces was entering its 3rd year. The drought had affected over 6 million people; 2.4 million have difficulty finding access to drinking water. August 4, 2013 set a new temperature record for Shanghai of 40.6°C, the warmest day since 1934. Also in August 2013 326 rivers had been cut off, 65 reservoirs dried up and 1,100 others left with dead storage levels in central China's Hubei Province, dubbed 'the land of a thousand lakes'. Up north, however, flooding was the problem. Ten rounds of rainfall battered North China's Shandong Province in July, and the province received 328 mm of rainfall in one month, a 50-year high (http://news.xinhuanet.com/english).
- ***Sahel***, *2012*: the Sahel region is a belt up to 1,000 km wide that spans Africa from the Atlantic Ocean to the Red Sea. At least one particularly severe drought has been confirmed each century since the 17th century. However, the frequency and severity of recent droughts stand out. The drought in 2012 came only two years after the previous one. In May 2012, UN warned that over 18 million people were facing hunger across eight countries in West

Africa including the Sahel region. A combination of failed crops, insect plague, high food prices, conflict and drought collectively caused the ensuing famine. (www.aljazeera.com; Wikipedia; www.huffingtonpost.com).

- ***United States hurricanes, 2005, 2012***: The consequences of the Hurricane Katrina (August, 2005) and the Superstorm Sandy (October, 2012) in the US have been analyzed in a Lloyd report (Lloyd, 2014). The report is calling for the industry to consider new catastrophe modelling after the harsh lessons of these events. It has been obvious from the IPCC reports that unless governments act now to reduce emissions, no one will be safe from effects of climate change. It is apparent that the poor will suffer most. The UN Climate Chief Christiana Figueres argued in March 2014: 'Devastating weather such as the flooding that hit England this winter and the fires that affected Australia last year will have a silver lining if it reminds politicians they must act on climate change.'
- ***United States 2012***: July 2012 was the hottest month in the United States since record keeping began in 1895, and 2012 was the warmest year overall, marked by historic high temperatures and droughts, above average wildfires, multiple intense storms. The 2012 drought impacted about 80% of agricultural land, making it the most severe drought since the 1950s (World Bank, 2012). About one-third of all Americans experienced 10 days or more of 38°C (100°F) temperatures (United States CAR, 2014).
- ***India** 2012–2014*:
  - In June 2012 the Brahmaputra River overflowed during monsoon rains, flooding more than 2,000 villages and forcing around 2 million people to leave their homes in the Assam state in the north east of the country. It was considered the worst flooding the state has seen since 2004. Assam's river island of Majuli experienced its worst flooding since 1950 (Wikipedia).
  - Himalayan flash floods occurred in August 2012 in the Himalayan region of Northern Indian states and Western Nepal. Landslides and flash floods were triggered by a sudden cloudburst which left 31 people dead while 40 are reported to be missing. The major hydroelectric power generators were shut down following torrential rains (a BBC video is found at http://www.bbc.com/news/world-asia-17973014).
  - Devastating floods were hitting Uttarakhand in Northern India in July 2013. Floods and landslides affected more than 4,000 villages. The early monsoon rains in the region were believed to be the heaviest in 80 years. According to figures provided by the Uttarakhand government, over 5,700 people were 'presumed dead' (Wikipedia). An 11-member expert panel was appointed in October 2013 at the direction of the Indian Supreme Court to determine whether Uttarakhand's hydropower projects influenced the causes and consequences of the flooding that occurred in 2013. The committee concluded that hydropower development significantly amplified the damage and found that existing oversight practices do not adequately account for how significantly power dams affect the Himalayan gorges where they are being built, and called on India to overhaul its policies and practices for approving new hydropower projects. Logically, the findings of the committee were condemned by the Central Electric Authority and the Central Water Commission (see further Chapter 10) (www.circleofblue.org/waternews/2014/world/).
  - Flooding on the Brahmaputra has brought death, displacement and disease to what has become one of India's poorest regions (March 2014) (www.theguardian.com/global-development/2014).

- ***Argentina***, *2013*: a violent flash flood hit the north eastern section of the Buenos Aires province and claimed the lives of at least 100 people in April 2013. The flooding was the result of extremely heavy rainfall (some 400 mm in La Plata in 2 hours, and 150 mm on the capital, Buenos Aires) and is said to be the worst flooding in La Plata's history (www.bbc.com/news/world-latin-america).
- ***Greenland***, *2013*: an all-time high temperature of 25.9°C was recorded in Maniitsoq on July 30 (www.tutiempo.net/en/Climate).
- ***Colorado, USA***, *2013*: In Boulder Colorado 430 mm of rain came in a few days in September 2013. This corresponds to one year of precipitation. This is called a 1000-year-event (NOAA, see www.climate.gov/news-features/event-tracker/historic-rainfall-and-floods-colorado).
- ***Mexico***, *2013*: two tropical storms hit Mexico on the same day, 16 September. One attacked from the Mexican Gulf and the other from the Pacific Ocean. 42 people were killed (Wikipedia, Hurricane Manuel).
- ***Philippines***, *2013*: The typhoon Haiyan that hit Philippines in November 2013 was the most powerful typhoon that has reached a land area with wind velocities reaching 380 km/h. Over 5,700 people died, around 600,000 people lost their homes and some 10 million people were affected in some way by the typhoon. It is now realized that not only the surface water temperature in the ocean is a critical factor. Both at the Haiyan and at the Katrina typhoon (or hurricane) – that hit New Orleans in 2005 – the water temperature far below the surface was unusually high. In early November 2013 the water temperature in the Pacific east of the Philippines was as high as 30°C some hundred meters below the surface, some 3–4°C higher than normal. This contributed to make the Haiyan typhoon so powerful. The scientific basis for this is discussed in Knutson *et al.* (2010). 'Typhoon Haiyan is a wake-up call for the international community to speed up efforts to fight climate change', UN Secretary-General Ban Ki-moon warned (Nov. 2013 in Vilnius, Lithuania) as estimates put the total affected at nearly 13 million, including over four million displaced and 2.5 million in need of food aid. The disaster offers a glimpse of the future if urgent action is not taken.
- ***Argentina and Brazil***, *2013*: Argentina had one of its worst heat waves in December 2013. Downtown Buenos Aires reached 37.8°C, which is about 9°C above average for late December (www.accuweather.com), while parts of Brazil were struck by floods and landslides following record rainfall that left 45 people dead and some 70,000 evacuated. At least seven cities set new records for most rain in a single month. Aimores, Minas Gerais (north of Rio de Janeiro), received 852 mm in December, more than 4 times the average. The previous record was 350 mm (http://earthobservatory.nasa.gov/IOTD/view.php?id = 82759).
- ***Australia***, *2014*: a record heat wave hit Australia in January 2014. The highest temperature during the heat wave 47.2°C was recorded in Keith West, South Australia. Melbourne (Victoria) set a record with four consecutive days of 41°C and above. Adelaide (South Australia) set a record with five consecutive days of 42°C and above. In January 2013 a record high was noted in Moomba, South Australia with 49.6°C. The weather maps on TV required a new color code! (Wikipedia, 'January 2014 South Eastern Australia heat wave').
- ***Extreme winter***, *Feb. 2014*: record-breaking snowfalls occurred in North Eastern America and Japan, while the Eastern Balkans in Europe were unseasonally warm.
- ***UK***, *2014*: This was the wettest winter on record since 1910. 4 of the 5 wettest years and the 7 warmest years on record in the UK have occurred in the 21st century.

- ***Afghanistan***, *2014*: at least 1,500 people got homeless after floods killed more than 100 across the country in April 2014 (http://reliefweb.int/disaster).
- ***California and Western States, USA,*** *2014*: The US has been engulfed in one of the worst droughts in recent memory (May 2014). Over 30% of the country experienced at least moderate drought. In seven states drought conditions were so severe that each had more than half of its land area in severe drought. Additionally, in California and Oklahoma, 25% and 30% of the states, respectively, suffered from exceptional drought, the highest severity classification. Under exceptional drought, crop and pasture loss is widespread, and shortages of well and reservoir water can lead to water emergencies. In the Southwest, concerns were less-focused on agriculture and more on reservoir levels. In Arizona, reservoir levels were just two-thirds of their usual average, while in New Mexico, reservoir stores were only slightly more than half of their normal levels. In Nevada the storage were reported to be at about a third of what one would expect (Hess-Frohlich, 2014). The situation in California may well be the most problematic of any state. The entire state was suffering from severe drought in July 2014, and 80% of all land area was under extreme drought, according to the US Drought Monitor (http://droughtmonitor.unl.edu). Drought in California has worsened considerably in recent years. Severe drought conditions covered the entire state. California Governor Jerry Brown declared a statewide drought emergency in January 2014 as the drought worsened. Conditions have not been this dry since the mid to late 1970s. The multiyear dry spell is described as one of the three worst droughts in over a century. An average of nearly 90% of the city of Bakersfield, California has been in a state of exceptional drought over the first seven months of 2014, more than any other large urban area.

  With the drought, the state is dealing with a 'year-round fire season instead of a seasonal fire season,' which obviously puts an enormous strain on water supplies. According to a recent University of California study, the drought will cost the state an estimated $2.2 billion and over 17,000 jobs. The economic impact will be even higher in California's Central Valley, where many of the cities with the worst drought conditions are located. The Central Valley is known for its vibrant agricultural industry, which is also a primary source of specialty crops such as fruits and nuts. In 2014 some 1740 km^2 (430,000 acres) has been left fallow due to the drought. Declining groundwater tables, due to excessive over-pumping during the state's extreme drought, have led to land subsidence and significant damage to roads, canals, aqueducts and pipelines. In September 2014 California senators have approved a bill to regulate groundwater in the state for the first time in its history. Companion legislation is going through the parliament's other house.
- ***Texas, USA,*** *2014*: In 2014 the majority of Texas has been experiencing drought conditions that started in October 2010. Most of the state has been under drought conditions for over three years. Climatologists have warned that Texas could be in the midst of a drought worse than the drought of record in the 1950s. 2011 was the driest year ever for Texas, with an average of only 14.8 inches (375 mm) of rain. 2011 also set new records for low rainfall from March through May, and again from June through August. The high summer temperatures increased evaporation, further lowering river and lake levels. The state experienced a short and rainy respite in the winter and spring of 2012, but by the fall of 2012 dry conditions had returned to much of the state. Those persisted until late in the summer of 2013, when a sustained rainy period lowered the percentage of the state experiencing drought. As of June, 2014, 70% of Texas was still in drought conditions, while 2% was in the worst two

stages of drought, either extreme or exceptional drought. The state's reservoirs are 67% full. The main culprit of the intense 2011 dryness is considered to be La Niña, which creates drier, warmer weather in the Southern US. The El Niño generally has the opposite effect. An El Niño weather pattern was predicted to bring some relief to the state in the winter of 2012–2013, but it failed to appear. In February 2013, the state climatologist told the Texas Legislature that high temperatures related to climate change have exacerbated the drought. The state's average temperature had increased by an average of about 1°C (2°F) since the 1970s. If El Niño predictions for late 2014 prove correct, winter rainfall in Texas could be substantial.

The drought has caused drain reservoirs, fuel wildfires, ruin crops, and put a real strain on the state's electric grid. Officials from ERCOT, Texas' electric grid operator, are also concerned. Nuclear, coal, and natural gas energy production all require large amounts of fresh water to cool equipment (see Ch. 13–14). High energy usage and scorching temperatures caused ERCOT to close one factory overnight during the height of the summer's heat. Officials worry that another spring and summer with low rainfall could mean the closure of some power plants.

- ***Balkan Peninsula***, *South East Europe, 2014*: Three months' worth of rain had fallen in only a few days in May 2014, producing the worst floods since rainfall measurements began 120 years ago. Bosnia-Herzegovina and Serbia were hit hardest, but flooding was also reported in Croatia, South Poland, Slovakia, and the Czech Republic. It is estimated that 500,000 people had been evacuated or left their homes. About 2,000 landslides caused by the torrential rain were reported, some on minefields left over from Bosnia's 1992–95 war. Official sources were quoted as saying that all mine warning signs had been moved (http://mashable.com/2014/05/18/flooding-balkans).
- ***Eastern Pacific***, *2014*: Hurricane Cristina was the 2014 Eastern Pacific hurricane season's third named storm and its second hurricane. It became the season's second Category 4 hurricane on June 12, 2014, marking the earliest occurrence of two Category 4 storms in that basin in modern records dating to 1971 (National Hurricane Center, USA, www.nhc.noaa.gov).
- ***South Asia*** *2014*: A shifting monsoon is likely to leave some regions under water, and others in worsening drought (web.worldbank.org/WBSITE), with major cities like Mumbai, Kolkata and Dhaka also facing increasingly intense cyclones. In South East Asia, Bangkok could be under water by 2030 or 2040.

This is a pattern of global change that it would be very unwise to ignore. There is no definite answer yet what is the contribution of climate change on the recent extreme weather events. However, the extreme weathers are consistent with what is expected from fundamental physics.

The emergence of climate prediction models can now provide opportunities to increase the lead times of early warnings. Seasonal climate outlooks help authorities to predict excessive or deficient rainfall. Traditionally historical data have been used to analyze hazard patterns. This is no longer sufficient, because hazard characteristics are changing as a result of climate change. Simply expressed: more severe events can happen more frequently in the future. There is a need for forecasting models in the complete time scale from the next hour to seasonal changes and further to decadal time scales to inform strategic planning, for example for coastal zone management, new building codes and retrofitting of infrastructures.

More severe weather events can happen more frequently in the future.

4.2.4 The tipping point

Despite the increase of extreme weather events global climate change has so far given rise mostly to relatively linear, predictable changes in the environment. However, when an ecosystem passes a certain point, a previously calm, often linear change process may suddenly become considerably more dramatic. Abrupt climate change, unlike gradual changes such as a steady increase in global temperatures, can cause rapid changes to physical, biological and human systems over just years or decades, far too fast for humans to adapt properly. Such non-linear process may involve *tipping points* and lead to an entire ecosystem collapsing. At a particular moment in time, a small change can have large, long-term consequences for a system, in other words ‘little things can make a big difference’.

> Despite the increase of extreme weather events global climate change has so far given rise mostly to relatively linear, predictable changes in the environment. However, when an ecosystem passes a certain point, a previously calm, often linear change process may suddenly become considerably more dramatic – a tipping point.

A number of possible tipping points have been defined by Lenton *et al.* (2008), for example the extent of the Arctic Sea ice, the volumes of the Greenland ice sheet and the West Antarctic ice sheet, the amplitude of the El Niño Southern Oscillation, the rainfall of the Indian Summer monsoon, the tree traction in the Amazon rainforest, and the volume of the permafrost. The tipping points have very different time frames. Both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (IPCC, 2014b). The world is already passing tipping points for abrupt, catastrophic and irreversible changes to the global climate. Some projected tipping points, such as the melting of Arctic permafrost, are unlikely to happen this century, but others, such as the collapse of Arctic summer sea ice, are already under way and accelerating. Other tipping points such as the collapse of the West Antarctic ice sheet could happen this century but are not yet well enough understood to predict. IPCC (2014c) expresses the concern in the following way: ‘Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases.’

Although large uncertainties remain, the world is not doing enough to prepare for and anticipate these types of threats. One important action is to develop early warning systems to buy humanity a few critical years to prepare for the worst impacts of abrupt climate change.

4.3 CLIMATE CHANGE IMPACT ON ENERGY

The power generation sector has a major influence on climate change. Also the reverse is true: climate trends will strongly influence the efficiency and capacity of the power sector.

Every year the International Energy Agency (IEA) publishes their World Energy Outlook. The 2013 version (IEA, 2013a) was released in November 2013 and presents a gloomy picture of the consequences of the increasing energy quest in the world during the coming decades. According to IEA the global energy demand will increase by one-third from 2011 to 2035. Demand grows for all forms of energy, but the share of fossil fuels in the world's energy mix falls only from 82% to 76% in 2035. Low-carbon energy sources (renewables and nuclear) meet around 40% of the growth in primary energy demand. Nearly half of the net increase in electricity generation comes from renewables (including hydropower, wind and solar energy).

Even with the renewable power development, fossil fuels will dominate the energy production 20 years from now.

CO_2 emissions from power plants will rise from 13.0 gigatonnes (Gt) in 2011 to 15.2 Gt in 2035, retaining a share of around 40% of global emissions over the period. (The World Bank (2012) stated that CO_2 emissions at present are about 35 Gt/year – including land-use change – and, absent further policies, are projected to rise to 41 Gt/year in 2020).

EXAMPLE

To illustrate how much 1 Gt is: a coal fired plant emits around 100 kg/GJ = 360 kg/MWh. This means that a 500 MW plant will emit around 180 ton of CO_2 per hour, or $1.5*10^9$ ton (Mt) in a year if operated at full capacity. Assuming that the plants are running at 2/3 of maximum capacity then 1 Gt is emitted by 1000 coal fired plants – each one with 500 MW – in a year.

Increasing penetration of low-carbon technologies and improvements in the thermal efficiency of fossil-fuelled power plants help to slow the growth in CO_2 emissions from the power sector (see further Chapter 11). Natural gas is frequently promoted for being relatively low in carbon emissions compared to oil or coal. Still low-carbon coal is fossil fuel. The new global energy market could make it harder to prevent dangerous levels of warming. The evolution of the power sector will be critical to meeting climate change goals, due to the sector's rapid growth and because low-carbon alternatives are more readily available.

The magnitude of future global coal demand growth is uncertain, particularly because of the varying stringency of environmental policies. According to IEA (2013a) OECD coal use falls by one-quarter by 2035 as coal is backed out of power generation. By contrast, demand expands by one-third in non-OECD countries – predominantly in India, China and the ASEAN region – despite China reaching a plateau after 2025. Globally, coal remains the leading source of electricity generation, though its share is expected to fall from 41% to 33% in 2035. But the message is more sobering for the planet, in terms of climate change. The United States' reduced reliance on coal will just mean that coal moves to other places. And the use of coal, now the dirtiest fuel, continues to rise elsewhere. China's coal demand will peak around 2020 and then stay steady until 2035, the report predicts, and in 2025, India will overtake the US as the world's second-largest coal user.

IEA warns that *only one-third* of the proved reserves of fossil fuels should be used by 2050 to limit global warming to 2°C, as many scientists recommend. Such restraint is unlikely without a binding international treaty by 2017 that requires countries to limit the growth of their emissions. Pushing ahead CCS (Carbon Capture and Sequestration, see Glossary) is one of the options. However, IEA does not believe that CCS will have any significant importance and predict that only 1% of all fossil fueled power plants will apply CCS in 2035 (the water demand for CCS will be discussed in Chapter 13). As the source of two-thirds of global greenhouse-gas emissions, the energy sector will be pivotal in determining whether climate change goals are achieved. Energy-related CO_2 emissions rise by 20% to 37.2 Gt in the New Policies Scenario from IEA, leaving the world on track for a long-term average temperature increase of 3.6°C, compared to pre-industrial levels. That will lead the world close to a catastrophical tipping point. Many governments have announced new measures to curb CO_2 emissions in the run-up to the UN climate summit in Paris in 2015, but they fall short of reaching the 2°C target. IEA re-emphasizes in the 2014 World Energy Outlook (IEA, 2014c) that emissions will rise by 20% to 2040, putting the world on track for a long-term global temperature increase of 3.6°C. Increasing power sector decarbonisation through 2040 by about 25% is key to achieving climate goals and would take the world halfway towards limiting the temperature increase to 2°C.

> Predictions by IEA of energy-related CO_2 emissions are leaving the world on track for a long-term average temperature increase of 3.6°C, compared to pre-industrial levels. That will lead the world close to a catastrophical tipping point.

4.3.1 Climate impact on energy production

At least three major climate trends are relevant to the energy sector (DOE/NETL, 2007; DOE, 2013a):

- increasing air and water temperatures;
- decreasing water availability in some regions and seasons;
- increasing intensity and frequency of storm events, flooding, and sea level rise.

Increasing temperatures, decreasing water availability, more intense storm events, and sea level rise will each independently, and in some cases in combination, affect the ability to produce and transmit electricity from fossil, nuclear, and existing and emerging renewable energy sources. These changes are also projected to affect demand for energy and as well as the ability to access, produce, and distribute oil and natural gas.

- *Thermoelectric power generation*: facilities are at risk from decreasing water availability and increasing ambient air and water temperatures, which reduce the efficiency of cooling, increase the likelihood of exceeding water thermal intake or effluent limits that protect local ecology, and increase the risk of partial or full shutdowns of generation facilities. For example, water temperatures in major European rivers and lakes have increased by 1–3°C over the last century (EEA, 2012) and the water temperatures are projected to increase with further increases in air temperature. Several power plants have already been forced to shut down in the US, India, France, and other countries due to lack of water or high water temperatures compromising cooling processes (World Bank, 2013). Thermal power plant projects are being re-examined due to their impact on regional water resources and their vulnerability to climate impacts. . For example, during the 2003 summer heat wave in Europe, more than 30 nuclear power plant units in Europe were forced to shut down or reduce their power production (Linnerud *et al.* 2011). See further Chapter 13.

- *Energy infrastructure located along the coast* is at risk from sea level rise, increasing intensity of storms, and higher storm surge and flooding, potentially disrupting oil and gas production, refining, and distribution, as well as electricity generation and distribution.
- *Oil and gas production*: both crude oil and unconventional oil and gas production are vulnerable to decreasing water availability given the volumes of water required for enhanced oil recovery, hydraulic fracturing, and refining. Rises in temperature will either increase or decrease the access to fossil fuel resources, for example decreased permafrost driving season in high latitudes, increased supply of oil and natural gas from the Arctic regions. See further Chapter 11.
- *Hydropower, bioenergy, and concentrating solar power* can be affected by changing precipitation patterns, increasing frequency and intensity of droughts, and increasing temperatures. More recurrent and longer droughts are threatening the hydropower capacity of many countries, such as Sri Lanka, China, and Brazil (World Bank, 2012). Still another problem is extreme raining, as experiences in India in 2013. Hydropower is discussed in Chapter 10.
- *Electricity transmission and distribution* systems carry less current and operate less efficiently when ambient air temperatures are higher. They may face increasing risks of physical damage from more intense and frequent storm events or wildfires.
- *Wind and solar power*: changes in renewable resource availability or productivity, such as changes in cloud cover, wind resources, and growing seasons on renewable resources.
- *Weather related disruptions*, such as changes in storm frequency/intensity: this will influence energy infrastructure (for example oil and gas drilling, pipelines and refineries, and power lines) and continuity of energy supply.

4.3.2 Climate impact on energy demand

Both in Europe and elsewhere there will be a reduced demand for heating and a strong increase energy demand for cooling. The number of heating degree days (HDD; see Glossary) in Europe has decreased by an average of 16 per year since 1980, from about 3450 HDD in 1980 to around 3000 in 2009, corresponding to some 0.5% decrease per year or 13% in 3 decades (EEA, 2012, Section 4.5.2). This decrease helps reduce the demand for heating, particularly in North and North West Europe. Climate change is projected to strongly increase energy demand for cooling in Southern Europe, which may further exacerbate peaks in electricity supply in the summer.

Energy is closely related to water (discussed in detail in Part IV of the book). The combined effects of population growth, climate change, and increasing hydrological variability will result in a heightened reliance on energy-intensive water supply options, such as water transport, treatment or desalination plants to supplement urban water supply. As temperatures rise, more water will be needed by the energy sector to meet both its own demand for water and to meet increased energy demands for the cooling of houses, offices, and factories.

4.3.3 Building more climate resilient energy

The DOE (2013a) report, Chapter 4, describes some important technologies to build more resilient energy systems. The main features include:

- *Energy demand*: enhanced demand side management and energy/water efficient equipment and buildings (see Chapter 21);

- *Oil and natural gas*: improved water efficiency and reuse and the use of alternative drilling and fracking fluids (see Chapter 11.1–11.2);
- *Cooling of thermoelectric plants*: improved cooling technologies and the use of non-traditional water supplies (see Chapter 13);
- *Hydropower*: improved turbine efficiency and reservoir management (see Chapter 10);
- *Bioenergy*: improved water use for biomass and refining (Chapter 12).

On top of this the development of wind and solar power technologies should be emphasized. The water demand for these technologies is negligible in comparison with traditional energy generation sources.

A continued research, development, and demonstration of climate-resilient energy technologies is certainly of importance.

4.4 CLIMATE MEETINGS

There has been an increasing insight among the general public that there is a climate change, and most probably this is caused by human activities. In a US National Assessment, 1998 it was stated: 'The scientific evidence that humans are changing the climate is increasingly compelling. Complex impacts affecting every sector of society, including, especially, the nation's water resources, now seems unavoidable …. In many cases and in many locations, there is compelling evidence that climate changes will pose serious challenges to our water systems.' The Second World Climate Conference, 1990 stated: 'The design of many costly structures to store and convey water, from large dams to small drainage facilities, is based on analyses of past records of climatic and hydrologic parameters. Some of these structures are designed to last 50 to 100 years or even longer.

The design and management of both structural and non-structural water resource systems should allow for the possible effects of climate change.'

> Records of past climate and hydrological conditions may no longer be a reliable guide to the future.

Climate change is a global issue and makes everything more challenging. Atmospheric greenhouse gases are well mixed, so emissions from anywhere contribute to the problem everywhere. Therefore unilateral actions are less effective and more difficult. It also creates a defense not to act: 'why should we reduce our emissions when other countries do not contribute with their actions?'

> Greenhouse gases are well mixed in the atmosphere. Emissions from anywhere contribute to the problem everywhere.

The 3rd UN World Water Development Report was launched at the 5th World Water Forum in Istanbul in 2009. Some of the key messages from this report are:

- 'There is mounting evidence in many regions of the impact of climate change on the Earth's hydrological cycle;
- Climate change is a basic driver of change in water resource availability;

- Lateral thinking 'out of the box' is essential both from those within the water sector and all others whose decisions have a major impact on water;
- Information about the status of availability and use of water and the potential impact of climate change is too poor to support informed policy decisions. There is an urgent need to gather, analyse and model data at all relevant levels – globally, regionally and locally – and to reserve the decline in observational systems;'

4.4.1 Kyoto 1997

At the famous climate meeting (the 3rd COP meeting) in Kyoto 1997 it was decided that the industrial nations (excluding the US) should decrease the emissions of GHG with 5.2%. This is still the only legally binding agreement on climate change. Instead of decreasing, the global emissions have increased by 45%, according to the EU commission. Emissions rose 5.9% in 2010, the largest in absolute terms in any year since the Industrial Revolution and the largest percentage increase since 2003 (UNEP, 2013). The combustion of coal represented more than 50% of the growth in emissions.

The Kyoto protocol was terminated in 2012 but prolonged until 2015, now called Kyoto 2. There were reasons to be pessimistic about the continuation of the international agreements after 2012. In the country with the largest energy use, the US, there was still in 2011 an increasing resistance to the 'scientific content' of climate change work. US Republican candidates running (October, 2011) for the presidency – Rick Perry and Mitt Romney – questioned that the primary cause of climate change is related to human activities. The Texas Governor Rick Perry talked about 'manipulated data'. Unfortunately they were not alone. In December 2011 Canada withdrew from the Kyoto agreement. According to the Kyoto protocol Canada should have decreased its GHG emissions by 6% between 1990 and 2012. Instead the emissions had increased by 35%.

The Kyoto 1997 protocol is still the only legally binding agreement on climate change.

4.4.2 Copenhagen 2009 – Cancún 2010 – Durban 2011

The world's policy makers and political leaders (114 parties) met in the Copenhagen Climate Convention Conference in 2009 (COP15). The participating nations could not agree on any new emission protocol after 2012. One of the major reasons for the failure of the 2009 Copenhagen Conference was the issue of carbon debt. High-income countries called for emission reductions in low-income countries, while the latter use the former's historical emissions, their carbon debt, as a reason for inaction. However, the parties agreed to call to submit voluntary emission reduction pledges for the year 2020. During 2010, many countries submitted their existing plans for controlling GHG emissions to the Climate Change Secretariat. Industrial countries presented their plans in the shape of economy-wide targets to reduce emissions, mainly up to 2020, while low-income nations proposed ways to limit their growth of emissions in the shape of plans of action. At the end of 2013 (UNEP, 2013) 42 high-income countries had responded to this call and submitted economy-wide greenhouse gas emission reduction pledges, 16 low-income countries have submitted multi-sector expected emission reductions, and in addition 39 other low-income countries have submitted pledges related to sectoral goals.

At the COP16 meeting in Cancún, Mexico (November 2010) the national plans were captured formally at international level under the banner of UNFCCC. This formed the basis for a collective effort to reduce emissions, in a mutually accountable way.

The climate meeting in Durban, South Africa (COP17) took place in December 2011, where it was decided to prolong the Kyoto Protocol until 2015. As one of the researchers responsible for the analysis of carbon emissions, Glen P. Peters, expressed: 'Each year that emissions go up there is another year of negotiations, another year of indecision.' Unfortunately, for many countries, the timing could not be worse. Europe had been facing a currency crisis of constitutional proportions. The US was preoccupied with jobs and growth. The Middle East and North Africa were consumed by questions of political reform. The US has not even signed the Kyoto protocol. China provided no promise of emission limitations unless they were coupled to the GNP development. Without the major emerging economies such as China, Brazil and India we would not have achieved much. IEA concluded in its World Energy outlook (IEA, 2011) that without any political commitments to limit GHG emissions the global temperature will approach a 6°C increase, which is 4°C more than the UN safety limit. IEA also noted that the window for meaningful action on climate change is now measured in years, not decades. We should have learnt that clear rules implemented properly can prevent the apparent build-up of risk.

4.4.3 Warsaw 2013

The COP19 meeting in Warsaw was a great disappointment. Before the summit started some key industrial nations backed away from commitments on carbon emission cuts. Only 134 out of 189 participating countries sent a government minister to the conference.

- Poland, the host country, provoked by arranging a coal industry conference in parallel with the Warsaw climate meeting.
- Australia sent no Government member. The Australian Prime Minister Tony Abbott had attempted to repeal Australia's carbon tax. In July 2014 the Senate voted to get rid of the mining tax. It is no secret that Abbott's Liberal Party was supported by the fossil fuel lobby and mining industry prior to the 2013 election. During his election campaign he once described the science behind human-induced global warming as 'absolute crap'. The Senate decision in July 2014 means that there is no longer a legal policy how to reach the minimum climate goal, to decrease the emissions by 5% until 2020, compared to the 2000 levels.
- Canada 'applauded' Australia's decision to change their climate plan.
- Japan announced that it will backtrack on its pledge to reduce its emission cuts from 25% to 3.8% by 2020.
- The overwhelming threat of climate change was also sidelined by UK's political parties. In a debate on increasing energy prices the blame was conveniently placed on 'green' regulations and charges.
- The Philippines was, in November 2013, reeling from the aftermath of Typhoon Haiyan with untold destruction. Their climate delegate Yeb Sano got a lot of attention from his emotional speech on the first day. He was fasting during the rest of the conference hoping that some concrete results would be obtained.

The ambivalence on public perceptions of climate change in the high-income countries causes the political parties to swing between action and inaction according to the flavor of the day.

Findings from opinion surveys, in contrast, suggest that climate change is as yet perceived by most people in industrial nations as a distant threat. Most see climate dangers as elusive and far removed from their lives, both in space and time. Citizens cannot grasp the significance of climate change because it is too abstract and not acute enough. Obsession with the immediate guides the illusion that we can afford to wait. Waiting will only prove that we are too late. The COP19 once more proved that energy politics is not a 'rational' technocratic process. It is based on values and deeper historical influences. Various pressure groups play a significant role.

The lack of vision and political will from the leaders of many high-income countries is not just harming their long-term competitiveness, but is also endangering efforts to create international co-operation and reach a new agreement that should be signed in Paris in December 2015.

Delay is dangerous. Inaction could be justified only if we could have great confidence that the risks posed by climate change are small. But that is not what climate science is telling us. The risks are huge.

4.4.4 IPCC meeting in Stockholm 2013

The IPCC Working Group 1 presented its contribution to the AR5 report (IPCC, 2013) in Stockholm in September 2013. As described earlier in this chapter, the report reveals hard facts that give many reasons for pessimism about the commitment of various political leaders to meet the climate goals. The message from the former UN chief negotiator Yvo de Boers is sobering when he stated that it looks almost impossible to reach the 2°C goal. The global emissions have reached new highs and there is no global agreement to handle the problems. The focus of the world leaders is far from sustainability and is more directed towards economic crises. The 2°C limit has been considered the maximum increase to avoid serious climate changes, but today few researchers believe that this limit will not be exceeded. Only the most optimistic scenario of the IPCC report, assuming drastic emission decreases, will provide the world with a chance to limit global warming to 2°C above the pre-industrial level.

The message in the 2013 IPCC report is basically the same as in the AR4 report (IPCC, 2007). The great difference is that six years have passed and the emissions of greenhouse gases have continued to grow. According to previous calculations the emissions should start decreasing in 2020. Instead the predictions will rather approach 4°C, even if all the countries will implement all the measures that they have promised. According to Bill Hare (CEO of Climate Analytics, Berlin): 'The problem is that the political ambitions of today will lead to considerably more emissions than what is required in 2020. In total the emission decreases in the rich countries 2–4 times less than required. The highest 'ambition gap' is not China or the low-income country world, but industrial countries with USA and Russia leading. Every year of delay is devastating. And the longer those pledges remain unmet, the more likely it is to get a 4°C world.'

When talking about 2°C we refer to the *global average*. In practice this means 3°C on land and 4–5°C in the Arctic regions. A 4°C global average means 6°C on land and more than 8°C in the Arctic area. As a result many regions on earth will be inhabitable. A 2°C world can probably be handled with a lot of effort and pain and global solidarity. A 4°C will have potentially catastrophic consequences and the world would be thrown into a dark era.

A global average of 2°C means 3°C on land and 4–5°C in the arctic regions. A 4°C global average means 6°C on land and more than 8°C in the Arctic area.

No nation will be immune to the impacts of climate change. However, the distribution of impacts is likely to be inherently unequal and tilted against many of the world's poorest regions, which have the least economic, institutional, scientific, and technical capacity to cope and adapt.

The difference between 2°C and 4°C is overwhelming. The German climate researcher Hans J. Schellnhuber (Potsdam Institute for Climate Impact Research) in a report to the World Bank (World Bank, 2012) states that 'the difference is the human civilization'. According to the report: 'The 4°C scenarios are devastating: the inundation of coastal cities; increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer, wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased frequency of high-intensity tropical cyclones; and irreversible loss of biodiversity, including coral reef systems. And most importantly: a 4°C world is so different from the current one that it comes with high uncertainty and new risks that threaten our ability to anticipate and plan for future adaptation needs.' Further evidence of the difference between the 2°C-world and the 4°C-world is summarized for all the large regions in the world in IPCC (2014a, Table 1).

The difference between 2°C and 4°C global warming is overwhelming. The difference is the human civilization.

Still, as predicted by IEA (2013a) we are heading towards a 4°C world. The World Bank report, published in November 2012 (World Bank, 2012), has been considered too alarmist by some critics. However, the IEA (2013a), published one year later, just confirms this pessimistic prediction. Given that uncertainty remains about the full nature and scale of impacts, there is also no certainty that adaptation to a 4°C world is possible. A 4°C world is likely to be one in which communities, cities and countries would experience severe disruptions, damage, and dislocation, with many of these risks spread unequally. The projected 4°C warming must not be allowed to occur – the heat must be turned down. Only early, cooperative, international actions can make that happen.

The 2°C target can still be reached in principle (UNEP, 2013). However, the problem is the time urgency and the great political inertia. Probably the decision makers have the impression that the 2°C target can be reached only by emission trading and some energy efficiency measures. This is far from sufficient. We need a dramatic shift in perspective. The official message has been that the rich countries ought to reduce their emissions by some 30% until 2020. So far they have only decreased marginally. Another condition has been that the rapid growth of emissions in China and other low-income countries will reach their peak in 2020. This will not happen, even if China has a massive development program on renewable systems and emission reductions. The peak will not appear before 2025–2030, according to Zou Ji at the National Center for Climate Change Strategy and International Cooperation PECE, Renmin University of China, Beijing.

4.4.5 New York 2014 – Beijing 2014

The urgency of the climate issue was expressed by the UN Secretary-General Ban Ki-moon as he invited world leaders, from government, finance, business, and civil society to Climate Summit 2014 on 23 September 2014 in New York, to catalyze climate action. He asked the leaders to bring bold announcements and actions to the Summit that will reduce emissions, strengthen climate resilience, and mobilize political will for a meaningful legal agreement in Paris in 2015. Actually the global emissions are expected to increase some 2.5% compared to 2013. For China the increase will be 4.5%. The global emissions in 2014 will be some 37 billion tons of CO_2, where China contributes with 10.4 billion tons, US with 5.2 and EU with 3.4 billion tons.

As Ban Ki-moon said in his opening speech: '*No one is immune from climate change, not even this UN Headquarter, which were flooded during superstorm Sandy.*'

The initial reaction of the summit has been positive. Several nations made commitments to significantly reduce carbon emissions and grow renewable energy. A Green Climate Fund is targeted to reach US$15 billion before the Lima climate conference in December 2014. So far around US$2.5 billion have been committed, notably 1 billion each from France and Germany. At the moment it is not obvious how much of this money is genuinely new and how much amounts to old promises with new names. US president Barack Obama pushed China to redraw the 'old divisions' between rich and poor nations and take on the responsibility of a 'big nation'. Chinese vice Premier Zhang Gaoli committed to double the country's contribution to a 'South-South' fund which will help low-income nations adapt to climate change. UK Prime Minister David Cameron urged a global agreement in Paris but failed to join France and Germany as leading EU economies pledged large sums to the Green Climate Fund.

A major declaration on forests was signed by 27 governments and more than 100 companies and organizations. It committed to end global deforestation by 2030. The World Bank also announced that over 1,000 businesses – along with 73 countries and 22 states, provinces and cities – have expressed their support for carbon pricing.

The Chinese President Xi Jinping and the US President Barack Obama met in Beijing on Nov 12 in connection with the APEC 2014 meeting. China and US made an unprecedented joint pledge to cut GHG emissions. This step is expected to drive more countries on board to negotiate a new agreement in Paris at the end of 2015. China announced that it intends to achieve peaking of CO_2 emissions around 2030 and to make its best effort to peak early. This is the first time that China has set up a time frame to cap its emissions. The nation also committed to increasing the share of non-fossil fuel energy to about 20% by 2030.

At the meeting President Obama announced a new target to cut GHG emissions to 26–28% below 2005 levels by 2025, a step forward from its previous pledge to cut emissions by 17% by 2020 from 2005 levels. Naturally the UN Secretary-General Ban Ki-moon was encouraged by the move and stated that this is 'an important contribution' to possible global change agreements in Paris in 2015. It is a remarkable moment when the two largest economies in the world stand shoulder-to-shoulder and make significant commitments to curb emissions. Still all the countries have to ensure that the commitments are equal to the urgency and magnitude of the problem.

4.4.6 The emission gap

UNEP has produced four assessments of the emission gap, the last one in November 2013 (UNEP, 2013), shortly after the IPCC (2013) was published. The emissions gap in 2020 is the difference between emission levels in 2020 consistent with meeting climate targets, and levels expected in that year if country pledges and commitments are met. UNEP seeks to inform governments and the wider public on how far the response to climate change has progressed over the past year. International efforts under UNFCCC are focused on keeping the average rise in global temperature to below 2°C, compared to pre-industrial levels. The UNEP report shows that there is a significant gap between political ambition and practical reality. Additional emission reductions are needed. Some of the conclusions of UNEP (2013) are:

- It becomes less and less likely that the emissions gap will be closed by 2020;
- The world will have to rely on more difficult, costlier and riskier means after 2020 of keeping the global average temperature increase below 2°C.
- In the period 2000–2010 the high-income country share of global emissions decreased from 51.8% to 40.9%. So, in 2010 the emissions from low-income countries were 59.1%. Today low-income and high-income countries are responsible for roughly equal shares of cumulative greenhouse gas emissions for the period 1850–2010.
- Global greenhouse gas emissions in 2020 are estimated at 59 $GtCO_{2e}$ (see Glossary) per year under a business-as-usual scenario (that only considers existing mitigation efforts). If implemented fully, pledges and commitments would reduce this by 3–7 $GtCO_{2e}$ per year. It is only possible to confirm that a few parties are on track to meet their pledges and commitments by 2020.
- A review of available evidence from 13 of the parties to the Climate Convention that have made pledges or commitments indicates that five – Australia, China, the European Union, India and the Russian Federation – appear to be on track to meet their pledges. (Note that the report was published only two months after the Warsaw meeting).

In the period 2000–2010 the high-income country share of global emissions was about 41% and the emissions from low-income countries about 59%.

4.5 RECENT CLIMATE ACTIONS

Is the battle lost? No, but the message has to be crystal clear that climate change is our most important challenge, in all countries. One way to make our politicians more willing to make decisions about sacrifices is that we all become aware of the problem. Yes, there are also technical solutions, but they do not come for free. We simply have to consume less. Should *we* or should our *children* and *grand-children* pay? The task is so obvious: a global deal covering all major economies is an absolute necessity. Naomi Klein in her landmark book "This changes everything" formulates the bottom line: "What the climate needs to avoid collapse is a contraction in humanity's use of resources; what our economic model demands to avoid collapse is unfettered expansion. Only one of these sets of rules can be changed, and it is not the laws of nature."

A global deal covering all major economies is an absolute necessity to meet climate change challenges. Should we *or should our* children *and* grand-children *pay?*

4.5.1 European Union

In January 2014 the EU Commission proposed a 2030 policy framework for climate and energy towards a low-carbon economy. Climate and energy targets for 2020 have already been set, but the 2030 target is aimed to ensure a longer term target for the Member States. EU leaders agreed in March 2014 to decide on the framework in October 2014 at the latest. A center piece of the framework is the target to reduce EU domestic greenhouse gas emissions by 40% below the 1990 level by 2030. To achieve the overall 40% target the emissions must be reduced by 43% compared to 2005. The EU ETS (emissions trading system) covers more than 12,000 power plants and manufacturing installations in the 28 EU member states, Iceland, Norway and Liechtenstein, as well as emissions from airlines flying between European airports. By setting its level of climate ambition for 2030, the EU can also engage actively in the negotiations on a new international climate agreement (the new agreement will be adopted in 2015, at the Paris climate conference, and implemented from 2020), that should take effect in 2020. Renewable energy will play a key role in the transition towards the target. The aim is to increase the share of renewable energy to at least 27% of the EU's energy consumption by 2030. The European Commission has also proposed a 30% energy savings target for 2030. New buildings should use half the energy they did in the 1980s and industry has to be about 19% less energy intensive than in 2001.

EU goals for 2030: (1) increase the share of renewable energy to at least 27%; (2) energy savings 30%; (3) industry using 19% less energy than in 2001.

4.5.2 United States

There are reasons to become more optimistic about the climate actions in the United States compared to a few years ago. A national poll for the Natural Resources Defense Council (NRDC) of 1218 registered voters was undertaken immediately after President Obama's State of the Union speech in 2013. It was found that 65% felt climate change is a serious problem and that a substantial majority supported President Obama using his authority to reduce carbon pollution.

On June 25, 2013, President Obama laid out a comprehensive plan to reduce GHG pollution, prepare the country for the impacts of climate change, and lead global efforts to fight climate change (EOP, 2013). *The President's Climate Action Plan*, which consists of a variety of executive actions grounded in existing legal authorities. President Obama set out a range of actions to tackle climate change and warned that the world must expect a stronger and more variable water cycle, with 'well-defined regions of haves and have-nots'. The President also warned that the planet would slowly keep warming for some time to come, noting that states and cities across the US are already taking it upon themselves to get ready. He concluded that 'a low-carbon, clean energy economy can be an engine of growth for decades to come'. However, the coal industry, Republicans and even some Democrats, particularly in coal-mining states, have characterised the move as anti-employment and even anti-American.

In a speech in Jakarta, Indonesia US Secretary of State John F. Kerry called on all nations to respond to 'the greatest challenge of our generation. … climate change ranks among the world's most serious problems – such as disease outbreaks, poverty, terrorism and the proliferation of weapons of mass destruction' (CNN, 17 Feb. 2014). Kerry also criticized climate-change deniers, saying 'a few loud interest groups' shouldn't be given the chance to misdirect the conversation. 'We should not allow a tiny minority of shoddy scientists and science and extreme ideologues to compete with scientific fact'.

The US Government, Department of State, released a far-reaching report in May 2014, the US Climate Action Report 2014 (United States CAR, 2014). More than 300 experts have worked together to compose this 300 page report, adding to the information given in the IPCC AR5 reports and still easily available for the layman. The report emphasizes climate impacts on the US but also describes several ways of international collaboration to meet the challenges of climate change. After the frustrations from earlier climate conferences it has a great symbolic value that the US now recognizes the severity of the climate threat. As expressed by Secretary of State Kerry in the preface: ‘All the scientific evidence is telling us that we cannot afford to reckoning with climate change. With each passing day, the case grows more compelling and the costs of inaction grow beyond anything that anyone with conscience and common sense should be willing to contemplate.’ The US is the world’s second-largest producer and consumer of energy, so climate actions in the country will be observed by any other country.

The US Government is now committed to act, and a significant proof was released by the White House in May 2014 (White House Energy Strategy, 2014). On top of the expected goals of supporting economic growth the report aims to deploy low-carbon energy technologies and lay the foundation for a clean energy future. The climate actions in the US are important, also for the international negotiations. As UNFCCC executive secretary Christiana Figueres remarked: ‘When the US leads action, it also encourages more rapid international efforts to combat climate change by strengthening political trust, building business momentum and driving new technology solutions.’

4.5.3 Climate actions in some other countries

The political will to act on climate change is rapidly building up. Some examples:

- *China*: After seeing widespread deaths from pollution in the 2014 winter, the World Bank President Jim Yong Kim expressed that ‘there’s a new spirit in China,’ and the political will to act on climate change is rapidly building, even if the UN-led talks falter. China as the world’s largest carbon emitter is setting ‘really, really aggressive goals’ on curbing climate-changing emissions. ‘China is moving to establish what could be the world’s biggest national carbon market’. ‘The fact that China is being so aggressive about their own carbon market is a really, really encouraging sign for a global (climate) agreement,’ according to Kim. ‘If China, the US and Europe could form the basis of a world carbon market, then low-carbon investment will surge and finally, finally we’ll have market mechanisms working to help us deal with climate change’.
- *Hong Kong*: The city has halved the number of cars in the city.
- *India*: The buses in New Delhi are now running on cleaner – though still not clean enough – natural gas.
- *Germany*: According to the World Bank, Germany is leading the world in growing its economy while reducing its carbon footprint.

4.6 THE GREENHOUSE EFFECT

The greenhouse effect is essential for life on Earth. Global warming occurs when certain gases in the atmosphere prevent sunlight from being reflected from the Earth. Ordinarily, sunlight that reaches the surface of the Earth is partly absorbed and partly reflected. The absorbed light heats the surface and is later emitted from the surface as infrared radiation. Gases that are not transparent to infrared radiation (carbon dioxide is one) collect this heat and keep it in the atmosphere, hence their name greenhouse gases. The Earth’s atmosphere is only 0.04% (400 ppm) carbon dioxide, but combined with other gases, this is enough to trap some 30% of the reflected heat, while the rest is radiated out to space, and maintain the Earth’s average temperature at about 15°C. If the greenhouse gases were not there the temperature at the surface of the Earth would be much colder, around –20°C, and we would have an ice planet.

> *Without any carbon dioxide in the atmosphere the average surface temperature on Earth would be –20°C.*

4.6.1 Greenhouse gas emissions

The most important greenhouse gas (GHG) is plain water vapour, which contributes for about 2/3 of the total natural greenhouse effect. Water vapour represents no risk in terms of increased greenhouse effect because it is short-lived and its average concentration is in principle constant in the course of time. Also, the clouds have a positive effect. Contrary to other greenhouse gases the water vapour in the clouds will bloc part of the solar radiation during the day. This will dampen the temperature influence.

Global warming is not the consequence of the natural greenhouse effect, but results from the additional influence of gases that are not part of natural equilibriums and that are emitted in increasingly larger quantities as consequence of human activities. The atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have all increased since 1750 due to human activity. In 2011 the concentrations of these greenhouse gases exceeded the pre-industrial levels by about 40%, 150%, and 20%, respectively, and now substantially exceed the highest concentrations recorded in ice cores during the past 800,000 years. The mean rates of increase in atmospheric concentrations over the past century are, with very *high confidence*, unprecedented in the last 22,000 years (IPCC, 2013, Chapters 5.2, 6.1–6.2).

CO_2 remains the major anthropogenic GHG accounting for 76% total anthropogenic GHG emissions in 2010, see Figure 4.1. 16% come from methane (CH_4), 6.2% from nitrous oxide (N_2O), and 2.0% from fluorinated gases (IPCC, 2013, Figure SPM.1). Annually, since 1970, about 25% of anthropogenic GHG emissions have been in the form of non-CO_2 gases [IPCC, 2014b, Ch. 1.2, 5.2].

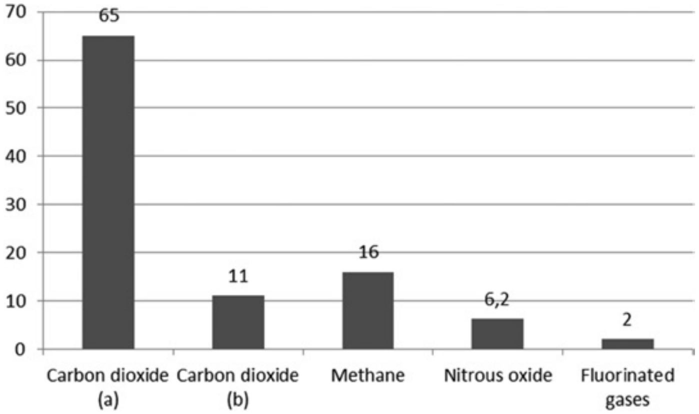


Figure 4.1 Relative annual anthropogenic GHG emissions in 2010 (in % of total emissions). CO_2 (a) is the contribution from fossil fuel combustion and industrial processes; CO_2 (b) from forestry and other land use. (*Data source*: IPCC (2014b), Figure 1.)

The strength of the emissions can be quantified as radiative forcing (RF), expressed in units watts per m^2 (W/m^2). RF is the change in energy flux caused by a greenhouse gas and is illustrated in Figure 4.2. There is an equation in thermodynamics, the Planck law. It defines the radiation as function of temperature. Max Planck proposed it in 1900. Planck's law can be used to calculate how much Earth must warm up to radiate more heat to space to balance the heat that has been trapped by the greenhouse gases.

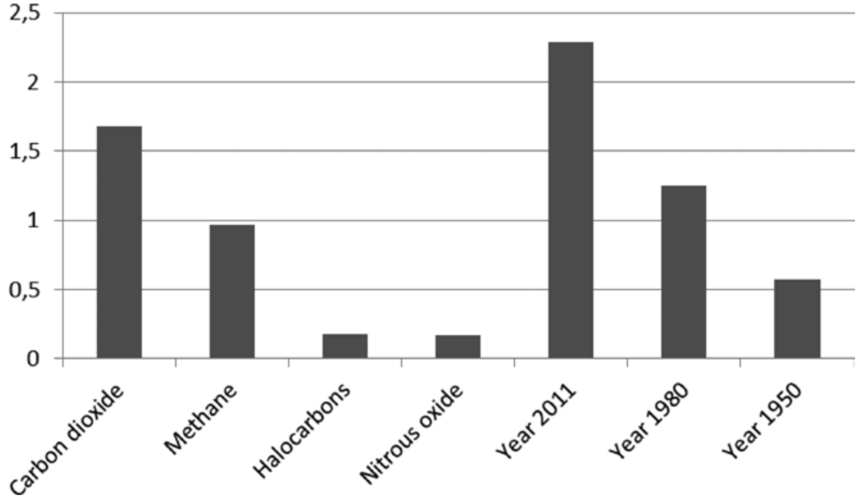


Figure 4.2 Comparison of radiative forcing (RF) for the key emitted components. The three bars to the right compare the total anthropogenic RF increase relative to 1750. *Data source*: IPCC (2013), Ch. 8.)

On the mid-to long-term the additional greenhouse effect can lead to excessive warming of the Earth surface, disrupting the regular climate and life patterns. Figure 4.3 depicts the GHG development in some countries from 1990 to 2012. The USA has been the biggest emission producer but is now overrun by China.

The relative contributions of the five largest emitters in 2012 are displayed in Figure 4.4.

In 2012 China and the USA together contributed with more than 40% of the total GHG emissions. Still, the emission per capita will give another aspect of the GHG producers, illustrated by Figure 4.5.

An interesting observation has been made by Heede (2014). Products from only 90 entities have been causing 2/3 of all CO_2 emissions since the middle of the 18th century, when the industrial revolution started in Europe. 50 of the entities are investor-owned companies, 31 are state-owned enterprises, and 9 are current or former centrally planned states. Out of the 90 companies 83 produce energy from fossil fuel (oil, coal or gas) and the other 7 entities produce cement. About 1/3 of the emissions are related to the top 20 corporations. It is worth noticing that half of all the emissions have taken place during the last 25 years, in a period when the causes of global warming have been on the agenda. It is not the corporations themselves that cause most of the emissions but the products, used for transportation, energy and heat generation, and industrial production. The contributions of 15 corporations are illustrated in Figure 4.6. In Chapter 11 we will have a closer look at the water footprint of some of these operations.

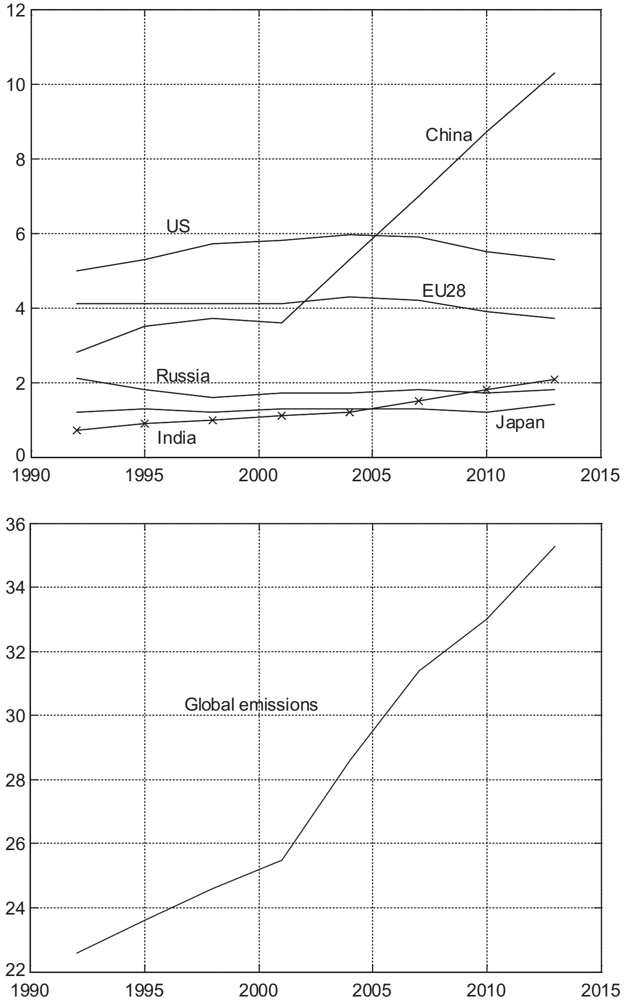


Figure 4.3 The development of carbon emissions from the largest emitter countries from 1992 to 2013, expressed in $GtCO_{2e}$/year. The global emissions during the same period are shown in the bottom diagram. (*Data source*: PBL (2014), Table 2.2.)

Calculating the cumulative volume of carbon dioxide emissions provides an opportunity to settle the question of historical responsibility for the damages caused by climate change. The US has the highest cumulative production of carbon emissions during the period 1902–2009, contributing 24–27% of the cumulative global volume, followed by the EU with 17–19%. China is nowadays the biggest source of carbon dioxide, but the cumulative volume of its emissions is still far behind with 10–12% (Kunnas *et al.* 2014). In other words, the main reason for a warming climate is the historical greenhouse-gas emissions of high-income countries. The emissions of the big four major contributors account for some 57–59% of the total cumulative footprint, leaving over 40% to the rest of the world, supporting the need for a global treaty put forward by high-income countries.

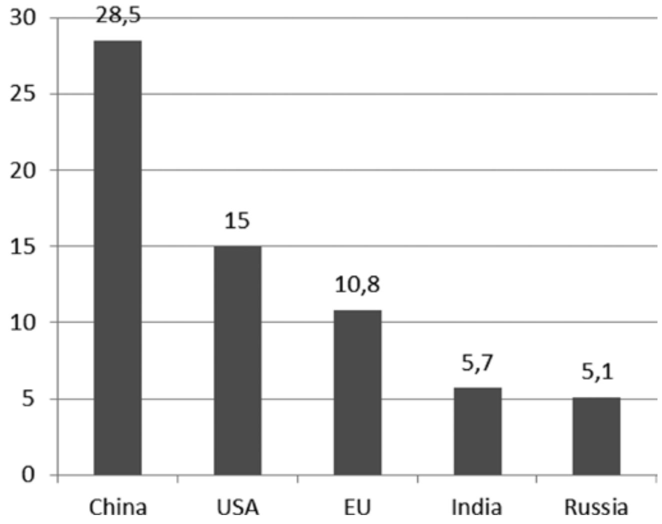


Figure 4.4 GHG emissions in 2012 from the five largest emitters, expressed as percent of the global emission. (*Data source*: PBL (2014).)

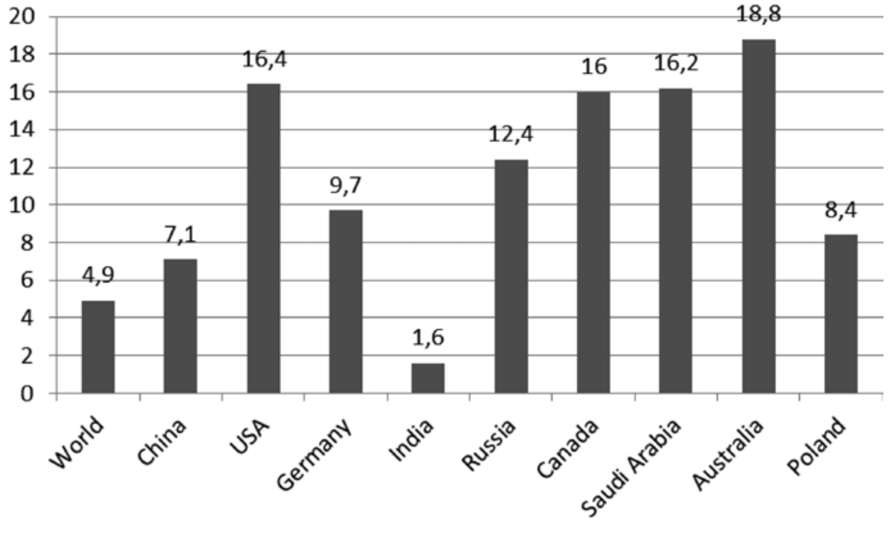


Figure 4.5 Emissions estimates per capita (tons of CO_2 per year) in some countries in 2012. (*Data source*: PBL (2014).)

What happens if more GHG are added to the atmosphere? There will be a new equilibrium. With more GHG the atmosphere will catch some of the heat radiation and will be warmer. The radiation out to space still will take place from a level in the atmosphere where the temperature is about –30°C. The interesting thing is that this level will be a few hundred meters higher than before. This will also imply that the surface temperature is higher.

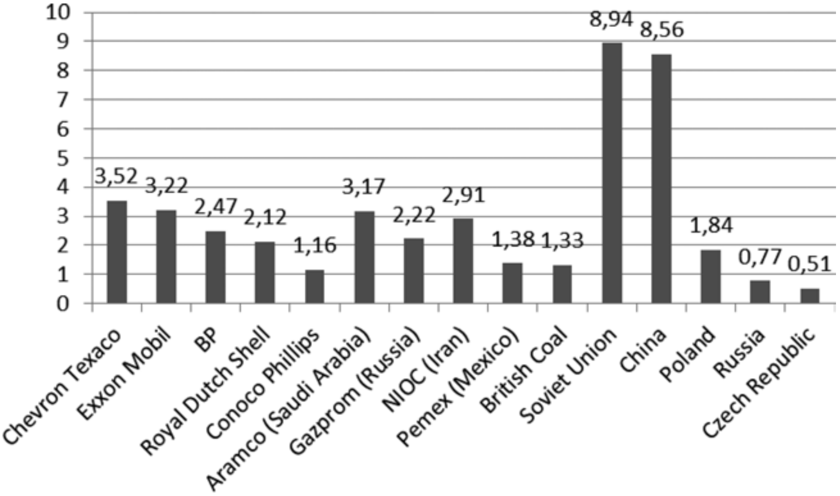


Figure 4.6 The producers of CO_2 emissions 1751–2010, given in percent of the total emissions. The first 5 are private corporations, the next 5 are state owned companies and the last 5 are centrally planned states. The 15 producers have delivered 44% of all emissions. (*Data source*: Heede (2014).)

During thousands of years the CO_2 content has been constant, around 280 ppm. It is possible to see an increase of the CO_2 content from the industrialization in the 1850s. The fast increase appeared after the World War II. In 1950 the CO_2 concentration was 310 ppm. In May 2013 the level of CO_2 in the atmosphere had risen above 400 ppm for the first time in over three million years. If 'business as usual' will continue the GHG level will be doubled before 2100, compared with the pre-industrial period. The extra heat that the GHG traps is a couple of W/m^2 of the Earth's surface. This is enough to warm the planet considerably. The obvious consequence is that the world must de-couple economic growth from our dependence on carbon-based energy systems, which currently provide 80% of our primary power needs.

We burn coal, oil and natural gas too quickly. As a comparison:

> We burn 8 times more fossil carbon than the carbon that can be used by all the vegetation on Earth.

It may look incomprehensible that the human can influence the CO_2 content and consequently the climate of the Earth. However, since only 4 out of 10,000 atmospheric molecules are CO_2 a simple calculation can illustrate the size of the gas content.

> If all the CO_2 could be collected at atmospheric pressure close to the Earth's surface it would be a thin layer of gas of only 3–4 m.

To influence such an amount of gas with the burning of fossil fuels suddenly looks comprehensible. The potential consequences of the greenhouse effect are described by different scenarios; they encompass major changes in agricultural production, the desertification of temperate areas, the melting of polar ice leading to raising sea levels and the consequent flooding of coastal areas, the spreading of new diseases, and many other serious problems. The media regularly report about these and other doomsday scenarios.

4.6.2 Early discovery of global warming

The Swedish scientist Svante Arrhenius (1859–1927) – see comments in 4.10 – and his colleagues in Stockholm started in the 1890s to study the mechanisms behind climate changes. Why had the ice ages appeared? From where did they come? Arrhenius concluded that there are mainly two gases in the atmosphere that determine the energy absorption: water vapor and carbon dioxide. The complexity of the mechanisms, however, was large. For example, an increased concentration of CO_2 will lead to higher average temperature. This in turn will increase the amount of water vapor, which will further amplify the energy absorption.

Arrhenius developed a theory to explain the ice ages, and in 1896 (see Arrhenius, 1896) he was the first scientist to state that changes in the levels of CO_2 in the atmosphere could substantially alter the surface temperature through the greenhouse effect. He was influenced by the work of others, including Joseph Fourier. Arrhenius used the infrared observations of the moon by Frank Washington Very and Samuel Pierpont Langley at the Allegheny Observatory in Pittsburgh to calculate the absorption of infrared radiation by atmospheric CO_2 and water vapor. Using the Stefan Boltzmann law he formulated his greenhouse law. In its original form, Arrhenius' greenhouse law reads as follows.

If the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression. This is expressed by:

$$\Delta T = \alpha \cdot \ln (c/c_0)$$

where ΔT is the temperature change, c the CO_2 concentration and α and c_0 constants. The formula is still useful today.

4.7 THE GREENHOUSE GASES

Four gases and two groups of gases with similar properties have been identified to contribute in a significant way to the greenhouse effect. They are:

- carbon dioxide (CO_2),
- methane (CH_4),
- nitrous oxide, also called dinitrogen oxide (N_2O),
- hydrofluorocarbons (HFCs),
- perfluorocarbons (PFCs) and
- sulphur hexafluoride (SF_6).

Carbon dioxide, methane, and nitrous oxide are natural greenhouse gases. They are produced and consumed in the course of natural processes and even without human intervention, their long-term atmospheric concentrations remain within established limits thanks to the natural feedback action between generation and sink activities.

HFCs and PFCs are families of artificial gases; they do not result from any natural process. SF_6 is also an artificial gas. All these gases are called fluorinated gases because they all contain fluor. Because these gases are not found in nature, no natural sinks able to absorb them could develop in course of time. Once released in the atmosphere, the artificial gases will remain there for centuries or even millennia until they are destroyed by physical processes.

4.7.1 Carbon dioxide

Carbon dioxide is a colourless gas, with no particular odour or taste. At standard temperature and pressure conditions (15°C, 1 bar) CO_2 has density 1.85 kg/m^3, or 1.52 times more than air. Therefore CO_2 tends to collect at low levels, on the ground or below. The gas is soluble in water at concentrations up to 2 g/liter. Even at low concentrations, from 1000 ppm (0.1% in volume), CO_2 can lead to headache and increase the respiration rate. This CO_2 concentration is found in plant greenhouses and is just three times higher than its current atmospheric concentration. Negative health effects can be felt from a 2% concentration, while at 5–10% the gas can be fatal.

The CO_2 concentration may seem small but it has a very long life in the atmosphere. Around 56% of all the CO_2 produced by human activities is still present in the atmosphere. This CO_2 is causing, directly or indirectly, some 80% of all global warming.

During the last 400–600,000 years atmospheric CO_2 concentration has varied between 180 ppm during glacial times and 280 ppm during the warmer interglacial periods. After 1750 the CO_2 concentration has increased to more than 400 ppm, and the increase is closely related to the burning of fossil fuels. Fossil fuel combustion activities are responsible for about three quarters of the CO_2 emissions that are related to human activity. The most important natural sinks for CO_2 are oceans and land, but together they can absorb only about half of all released CO_2. Considering that fossil fuels are the primary sources of energy worldwide, in particular for electricity generation, heating, and transportation, any measure oriented to reducing emissions by limiting the amount of used fuels would have profound consequences on modern societies.

4.7.2 Methane

Methane (CH_4) is the second most important gas among those contributing to the greenhouse effect, to which it accounts globally for approximately 18%. Methane is an odourless and colourless gas with density relative to air 0.6, that is, it is lighter than air so it rises when released.

The concentration in the atmosphere is 1.77 ppm compared to 0.72 ppm during the pre-industrial time, an increase of more than 150%. If the effect is measured for a full century, then methane has about 60 times higher ability to absorb heat compared to CO_2. Different to CO_2 methane does not have natural sinks so there is no natural methane cycle. Fortunately the methane does not remain in the atmosphere as long as the CO_2. The gas tends to decay quite rapidly by oxidizing in the atmosphere, leaving as final products water and CO_2.

Unlike other greenhouse gases, methane can be used to produce energy since it is the major component (95%) of natural gas. Consequently, for many methane sources, opportunities exist to reduce emissions cost-effectively or at low cost by capturing the methane and using it as fuel, see further Chapter 18.

Methane is produced in anaerobic processes (absence of oxygen), both man-made and natural anaerobic environments in water bodies (such as rice fields) and wetlands. This fact makes it crucial to avoid any leakage of methane in biogas production units.

The share due to human activities of the total methane emissions are estimated to be about 50–60%, from the wide-scale use of fossil fuels to rice growing and cattle farming. About

15–20% emissions result from enteric fermentation, a digestive process in herbivores such as cows and sheep but also of termites, where microorganisms break down carbohydrates into simpler molecules that can be used as food. Also the decomposition processes of the waste from herbivores are an important methane source.

Additional important methane sources are open landfills, with worldwide emissions estimated to 40 Mt/year. In this case methane is generated from decomposition under anaerobic conditions. Methane emissions from the energy sector are estimated to be 15–20% of the total. The gas can be released in natural gas fields or from pipelines leakages and small quantities of methane are produced during incomplete fuel combustion. Methane is the major component of natural gas and is present in association with other fossil fuels, mainly in coal mines where it must be ventilated away, otherwise representing a risk for explosions.

In a report from the International Siberian Shelf Study there is now evidence that massive deposits of sub-sea methane are bubbling to the surface as the Arctic region becomes warmer and its ice retreats. Areas of sea foaming with gas bubbling up through ‘methane chimneys’ rising from the sea floor have been observed north of Siberia. It is believed that the sub-sea layer of permafrost, which has acted like a ‘lid’ to prevent the gas from escaping, has melted away to allow methane to rise from underground deposits formed before the last ice age.

4.7.3 Nitrous oxide

Nitrous oxide or dinitrogen oxide (N_2O), also known as laughter gas, is a colourless gas with a sweetish odour. Its density relative to air is 1.5. Nitrous oxide contributes to the global greenhouse effect by about 6%. The N_2O is around 300 times more efficient to absorb heat compared to CO_2. The atmosphere contains only a small amount of the gas, but it will stay in the atmosphere for about 150 years.

In nature, N_2O is mainly emitted by biological sources in soil and water, in first place as a consequence of the microbial nitrification and denitrification processes. It is very difficult to quantify these emissions because the related mechanisms are not yet fully known, the involved factors are complex and the reactions take place in different ecosystems. The most important non-natural sources of N_2O are agriculture, fertilizers and pastures in tropical regions, biomass combustion, and some industrial processes such as the production of nitric acid and adipic acid. Nitrous oxide is also produced from air nitrogen during the combustion of fossil fuels at high temperatures. Compared to the pre-industrial time there is about 20% more N_2O in the atmosphere today (IPCC, 2007).

N_2O is primarily removed in the stratosphere by photolysis, that is breakdown by sunlight. This reaction is a primary source of nitrogen oxides which play a critical role in the control of the quantity and distribution of stratospheric ozone.

The atmospheric distribution of ozone and its role in the Earth’s energy budget is unique. In the lower parts of the atmosphere – the troposphere and lower stratosphere – ozone acts as a greenhouse gas. Higher up in the stratosphere there is a natural layer of ozone concentration. This layer absorbs ultra-violet radiation. This ozone plays an essential role in the stratosphere’s radiative balance and at the same time filters this potentially damaging form of radiation.

4.7.4 Artificial gases

The hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) appear in very small quantities in the atmosphere. However, some of them absorb heat extremely efficiently. For example, dichlorotrifluoroethane (also called R123 or HCFC-123) that has been used in cooling technology can absorb heat 10,000 times more efficiently than CO_2. The artificial gases can remain in the atmosphere for several centuries.

HFCs ($C_xH_xF_x$) have been designed as efficient refrigeration gases to substitute chlorofluorocarbons (CFCs, $C_xCl_xF_x$) after these were found to have a negative impact on the ozone layer of the atmosphere. HFCs have no negative influence on the ozone, but after their introduction they strongly contribute to the greenhouse effect.

PFCs (C_xF_x) are used by a number of industrial applications in the aluminium, electronic and electrical industries, as well as flame-quenching in fire protection systems and fire extinguishers.

SF_6 is used in the electrical industry as insulator in high voltage switchgear. It is a perfect dielectric gas because it is chemically stable, non flammable, non explosive, non toxic, inert and non aggressive towards the materials it comes in contact with. The electric power level that can be switched off in a sealed SF_6 atmosphere is 3–5 times higher than in air, which means that SF_6 switchgear can be built in confined spaces. This is today particularly important for urban power distribution networks because of very high land costs, the growing demand for electrical power, and the notable difficulties to build large, open-air power distribution substations in built-up areas. No SF_6 substitute is currently available and the electrical industry prefers to pay extra attention to contain atmospheric leakages of this gas rather than risking a total ban.

4.8 THE GLOBAL WARMING POTENTIAL

In subsequent chapters we will compare the carbon footprint of the water cycle. This will require a metric that can quantify the GHG potential of different energy requirements. The Global Warming Potential (GWP) has been defined and makes it possible to make a simple comparison of the effect of different greenhouse gases on the climate. The basic definition of the GWP defines the relative quantity of CO_2 that, if released into the atmosphere, would trap heat radiation in the same way as the considered GHG. IPCC describes the GWP as 'a measure of the relative radiative effect of a given substance compared to another, integrated over a chosen time horizon'. In the IPCC Fourth Assessment (AR4) the GWP is used more cautiously with several arguments presented against the use of a simple coefficient to compare the action of different gases. However, IPCC also recognizes the need to have a simple definition in order to encourage the practical use of the comparisons of the impact of the different GHG. For example, for methane GWP-100 is 28, which means that the impact of methane during one century is 28 times higher than that of CO_2. For the period 20 years (GWP-20) the methane impact is 84 times that of CO_2. The global warming potentials GWP-20 and GWP-100 for the main greenhouse gases are listed in Table 4.2.

Table 4.2 Global warming potential for the main greenhouse gases.

Greenhouse gas	GWP-20	GWP-100
Carbon dioxide	1	1
Methane	84	28
Nitrous oxide	264	265
HFC (39 gases)	1–10800	1–12400
PFC (13 gases)	1–8210	1–11100
SF_6	17500	23500

Source: IPCC (2013), Appendix 8A.

The IPCC estimates the accuracy for GWP values to be in the range of +35%.

In the definition of an index for the comparison among different gases, CO_2 is taken as reference because it has the least relative impact of all the greenhouse gases and is conventionally assigned the value GWP = 1. The overall importance of CO_2 despite its minimal GWP is due to the very large emitted quantities, much higher than for the other greenhouse gases. The coefficients commonly used to compare different gases are the GWP-100, formally decided in 1997 based on IPCC earlier reports from 1994 and 1995. For simplicity's sake, the index '100' is often dropped and the indication is simply 'GWP.' The GWP values have been updated in IPCC (2013). Because of the time period chosen it is necessary to be careful about interpreting the greenhouse effect. Often statements like 'the impact of methane is 60 times higher than CO_2' can mislead, since the time period is not given.

4.8.1 Estimating global warming potential

The estimation of the GWP coefficients is not simple and straightforward. Because of the very long timescale of the atmospheric decay of the greenhouse gases, and considering that these phenomena started to be investigated recently, the effect of particular gases cannot be measured or otherwise observed directly but only simulated with the help of computer models. Uncertainty is particularly high about the fluorinated gases, because they have existed for only a few decades and there isn't sufficient knowledge of their long-time behaviour in the atmosphere. On the contrary, the long-time behaviour of the natural gases is better understood because it can be traced back in history and the theoretical models routinely verified with experimental data.

The GWP coefficients can now convert the emissions of different gases to common indicators. The GWP coefficients have direct economic impact for greenhouse gas emissions and a slight change in the revision of a GWP coefficient may bring effects potentially worth millions Euro at a national level.

To indicate the transfers of carbon to the atmosphere, as in the case of emissions from combustion, it is also customary to refer to CO_2. Mass quantities of CO_2 are often used also to indicate carbon stored in the atmosphere. In the literature it is referred to either carbon or carbon dioxide so it is important to pay attention to what is what in each particular case. The element carbon has atomic mass 12 and oxygen 16, so the mass relation between C and CO_2 is 12/44. In other words, one tonne of carbon corresponds to 3.67 tonnes of CO_2. The CO_2 emissions into the atmosphere are usually measured in metric tonnes (tCO_2) and sometimes Tg (1 Tg = 1 Gt) (see Appendix 1). One tonne of CO_2 is produced by the combustion of about 375 kg hard coal or of 507 m^3 of methane.

4.9 FRUGALITY

Frugal means inexpensive (from Latin *frugalis*, meaning 'fruits of the earth, produce'). In order to mitigate climate change we have to think in terms of reduction, efficiency and economy. The concept of efficiency has to penetrate all thinking, from regulations to urban planning, agriculture, industry, and personal habits. Water can be used more efficiently in agriculture (such as irrigation management and other water savings strategies), in industry and in domestic life.

4.9.1 Efficiency

To achieve reduction in emissions will require changes and actions at many levels. The interactions between water, energy, land use and biodiversity require a more integrated approach. Tools to understand and manage these interactions remain limited, but benefits of integrations are apparent in:

- improved energy efficiency and cleaner energy sources;
- reduced energy and water consumption in urban areas through greening cities and recycling water;
- sustainable agriculture and forestry.

- *Investments*: Large changes in investment patterns are required (IPCC, 2014a).
  - Over the next two decades (2010 to 2029), annual investment in conventional fossil fuel technologies associated with the electricity supply sector is projected to decline while annual investments in low-carbon electricity supply (such as renewables, nuclear and electricity generation with carbon capture and storage, CCS) are projected to rise. CCS is further discussed in Chapter 13.
  - According to the International Atomic Energy Agency (IAEA, 2013) there will be a continued expansion of nuclear power until 2030, despite the slow-down of investments after the Fukushima nuclear accident caused by the earthquake and tsunami in Japan in March 2011. Nuclear capacity is expected to increase anywhere between 435 and 720 GW_e in the IAEA projections. Climate change mitigation is one of the key reasons for this expected nuclear reactor investment. Nuclear power is also considered as an interesting energy supplier for desalination facilities and to be a buffer capacity when hydropower capacity will fluctuate as a result of climate change. Of course the investments in nuclear power will be decided on national levels.
  - Annual incremental energy efficiency investments in transport, buildings and industry is projected to increase by about US$ 336 billion (limited evidence, medium agreement), frequently involving modernization of existing equipment (IPCC, 2014a, Ch. 13.11, 16.2.2).
- *Industry*: In 2010, the industry sector accounted for around 28% of final energy use, and 13 $GtCO_2$ emissions, including direct and indirect emissions as well as process emissions, with emissions projected to increase by 50–150% by 2050 unless energy efficiency improvements are accelerated significantly (IPCC, 2014a, Ch. 10). The industrial emissions are currently greater than emissions from either the buildings or transport end-use sectors. The energy intensity of the industry sector could be directly reduced by about 25% compared to the current level through the wide-scale upgrading, replacement and deployment of best available technologies, particularly in countries where these are not in use and in non-energy intensive industries.
  - *GHG emissions*: CO_2 emissions dominate from industry. There are also emissions from non-CO_2 gases. CH_4, N_2O and fluorinated gases from industry accounted for emissions of 0.9 $GtCO_{2e}$ in 2010. A key action would be the reduction of hydrofluorocarbon emissions by process optimization and refrigerant recovery, recycling and substitution (IPCC, 2014a, Tables 10.2, 10.7).
  - *Material use*: recycling and re-use of materials and products, and overall reductions in product demand could help reduce GHG emissions.

  - Many emission-reducing options are cost effective and profitable. In the long term, a shift to low-carbon electricity, new industrial processes, radical product innovations could contribute to significant GHG emission reductions. Lack of policy and experiences in material and product service efficiency are major barriers (IPCC, 2014a, Ch. 10).
  - Systemic collaborative activities across companies and sectors can reduce energy and material consumption. Applying cross-cutting technologies (for example more efficient motors and engines) and measures (such as reducing air or steam leaks) in both large energy intensive industries and small and medium enterprises can improve process performance and plant efficiency cost-effectively (IPCC, 2014a, Ch. 10).
- *Bioenergy* can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems. In some regions, specific bioenergy options, such as improved cook stoves, and small-scale biogas and bio-power production, could reduce GHG emissions and improve livelihoods and health for large groups of people (IPCC, 2014a, Ch. 11). More is discussed in Chapter 5.

In many industrial operations, climate control in buildings, power generation automation and advanced control will play a major role to make the operations more energy efficient. On-line measurements and automatic monitoring play an increasing role in bringing knowledge from data.

4.10 CHAPTER SUMMARY – THE URGENCY

> *The best time to plant a tree was 20 years ago. The next best time is today.*
> Chinese proverb.

Human-caused climate change is happening now. This is the overwhelming consensus among climate scientists. Water and climate are so tightly interconnected that any climate action has to be coordinated with water actions. Adaptation is starting to occur, but with more focus on reacting to past events than on planning for a changing future. Yet a fringe minority of our populace – primarily lobby groups in rich countries – clings to an irrational rejection of well-established science. This virulent strain of anti-science infects politicians, newspapers, and what we see on TV. Climate change is real and we must respond to it. We can no longer believe that the climate challenge can be solved ‘later’, when financial crises and unemployment have been solved. The issue of climate change is acute and so extensive, so we must deal with the climate crisis now and we must do it in a way that also contributes to solutions to other serious social problems. It has to be emphasized that it is not economic growth in itself that determines a society’s climate impact. It is the content of the growth, in other words what kind of economic activities that contribute to the growth. When we build our cities, is it done in a sustainable way? Are we eating food that has been produced and transported in a way that energy and water use has been taken into consideration? Do companies get incentives to operate more efficiently and use natural resources more efficiently? What can we do as individuals – our lifestyle and our influence on political decisions – and what should be done by our governments?

The World Bank President Jim Yong Kim believes the slow-moving UN climate change negotiations, which aim to build a new global climate treaty in 2015, to take effect in 2020, ‘are crucial but clearly not enough, and that delaying action on climate change until the new treaty takes effect is a lame excuse in the face of what we're about to hand to our children. What's needed is hard work to scale up the climate-friendly changes that are happening now but are insufficient, while continuing to push our leaders to sign global agreements'.

Some further ways to reduce carbon emissions and water scarcity are discussed in Chapter 22. As expressed by former US Vice President Al Gore in July 2014: 'climate change is the biggest challenge our civilization faces'. As noted by Achim Steiner (UN Under-Secretary-General, UNEP Executive Director): 'From a technical standpoint, meeting the 2°C target remains possible: it will take a combination of full implementation of current national pledges and actions, a scaling up of the most effective international cooperative initiatives, and additional mitigation efforts at the country level' (UNEP, 2013).

Both IPCC and IEA (2013a) remind that the future is not determined – 'the future is unwritten', as the punk musician Joe Strummer wrote in 1982. The researchers can predict the consequences of the GHG emissions but are no fortune-tellers about political decisions and production of future emissions. As scientists we may not remain on the sidelines. If we don't engage in the climate debate, we leave a vacuum to be filled by those with short-term self-interests. As expressed by Ken Caldeira of the Carnegie Institution for Science: 'the only ethical path is to stop using the atmosphere as a waste dump for greenhouse gas pollution'. We cannot remain quiet in the face of the great threats. On top of more efficient energy use, three major types of actions are needed:

- A determination to achieve international agreements on climate actions;
- More support for renewable energy;
- A refined CO_2 tax.

The problem isn´t just politics, it is human nature. We value the present and discount the future. We have to recognize this limitation and transcend it and change the way we live today. In a recent poll (2014) in my Swedish hometown people were asked answer what to do about the climate. 64% of 1250 people answered 'I am doing sufficiently already for the climate. It is sufficient.' We need to get the message across!

4.11 RECOMMENDED READING

4.11.1 A note on Svante Arrhenius, a GHG pioneer

Arrhenius' high absorption values for CO_2 met criticism by Knut Ångström in 1900, who published the first modern infrared spectrum of CO_2 with two absorption bands. Arrhenius replied strongly in 1901 (Annalen der Physik), dismissing the critique altogether. He touched the subject briefly in a technical book titled Lehrbuch der kosmischen Physik (1903). He later wrote Världarnas utveckling (in Swedish) (1906), with the German translation Das Werden der Welten (1907), and the English translation Worlds in the Making (1908) directed at a general audience, where he suggested that the human emission of CO_2 would be strong enough to prevent the world from entering a new ice age, and that a warmer earth would be needed to feed the rapidly increasing population. Arrhenius clearly believed that a warmer world would be a positive change. From that, the hot-house theory gained more attention. Until about 1960 most scientists dismissed the hot-house/greenhouse effect as implausible for the cause of ice ages as Milutin Milankovitch had presented a mechanism using orbital changes of the earth (Milankovitch cycles). Nowadays, the accepted explanation is that orbital forcing sets the timing for ice ages with CO_2 acting as an essential amplifying feedback (see Wikipedia.com)

Arrhenius estimated that halving of CO_2 would decrease temperatures by 4–5°C and a doubling of CO_2 would cause a temperature rise of 5–6°C. In his 1906 publication, Arrhenius adjusted the value downwards to 1.6°C (including water vapour feedback: 2.1°C). Recent (2007) estimates from IPCC say this value (the climate sensitivity) is likely to be between 2 and 4.5°C. Arrhenius expected CO_2 levels to rise at a rate given by emissions in his time. Since then, industrial carbon dioxide levels have risen at a much faster rate: Arrhenius expected CO_2 doubling to take about 3000 years; it is now estimated in most scenarios to take about a century.

In 1903 he became the first Swede to be awarded the Nobel Prize in chemistry. Actually he was a physicist but is considered to be a founder of physical chemistry. The Arrhenius equation is a simple, but remarkably accurate, formula for the temperature dependence of the rate constant, and therefore, rate of a chemical reaction. A historically useful generalization supported by the Arrhenius equation is that, for many common chemical reactions at room temperature, the reaction rate doubles for every 10°C increase in temperature. This is also valid for aerobic growth in biological wastewater treatment.

4.11.2 More to read

There are several good books describing climate change that are understandable for the layman. Flannery (2005) is an excellent book for the layman on climate change. Houghton (2012) describes in detail the greenhouse effect and Kump (2002) discusses the influence of carbon dioxide. National Academies (http://nas-sites.org/americasclimatechoices) regularly publish interesting updates and explanations of climate change. Dieter Helm's book (Helm, 2013) makes a sobering read. Being an economy professor he notes that global efforts to reverse CO_2 emissions have achieved essentially nothing in the last quarter of a century. The distinguished former director of the NASA Goddard Institute for Space Studies, James Hansen has written a book that is a 'must read' (Hansen, 2011). The recent article Higgins (2014) is an excellent and easily readable account of handling climate change.

The Bishops' conference of the Church of Sweden has produced a thought provoking position paper (Bishops' letter, 2014) about the climate and our personal responsibility. It is further discussed in Chapter 22. The National Geographic magazine has devoted several issues on climate change, in particular National Geographic (2004, 2007a). National Geographic (1981) is an early report on the energy issues. National Geographic (2007b) illustrates some strategies to reduce the GHG emissions. The droughts in the Western US are described and illustrated in the October 2014 issue of National Geographic magazine. The National Geographic September 2013 issue is devoted to the rising sea threat.

UN World Water Development Report (WWAP, 2011) summarizes the influence of climate change on water resources. The International Siberian Shelf Study (ISSS, 2008) describes the methane release in the Arctic area. EPA (2010a) gives detailed estimates of methane and nitrous oxide emissions. Carbon storage is discussed in a comprehensive report CCS (2011) and is further discussed in Chapter 13.4. Smith *et al.* (2009) contains several scientific papers on the effects of climate change on urban water and wastewater utilities.

Higher gasoline taxes could prove to be a fundamental part of any climate action plan, as discussed in detail in the book Sterner (2011). The book challenges the conventional wisdom that gasoline taxation has a disproportionately detrimental effect on poor people.

5 Population

Educate the girls and the problem of population explosion is halfway to being solved.

Unknown

The challenge of water supplies starts with the sheer number of people. In 1950 the world population was 2.5 billion. Water scarcity, drought and hunger have always affected people in dry countries. The green revolution combined new crop breeds, fertilizers and water. This made it possible to feed so many more people. In 2000 some 500 million people (or 8% of the global population) lived in countries chronically short of water. It is feared that

> in 2050 some 45% of the global population, around 4 billion people, will suffer from water scarcity.

Conservation must be an issue for everybody, because the best way to increase the supply of water is to save it as much as possible, that is, to be frugal. Advances in technology should increase the reuse of water and lower the cost of desalination of sea water.

Global warming and climate change are closely related to water availability. The findings of the IPCC AR5 are crystal clear (IPCC, 2014b, page 8): 'Globally, economic and population growths continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply'.

5.1 THE POPULATION GROWTH

The issues associated with population growth seem endless; poverty, food and water supply, world health, climate change, deforestation, fertility rates, and more. The world population was around 1 billion around 1800. It had doubled in 1930. Another billion people inhabited the earth in 1960. The 3 billion population in 1960 doubled to 6 billion in 1999. Today the population has exceeded 7 billion (if the projections by the UN are correct, this happened on 31 October, 2011) and UNPD (the UN Population Division) estimates that the population will have passed the 9 billion mark in 2050. The population of Africa recently passed the 1 billion level.

We were 7 billion in 2011 and will probably be 9 billion by 2050.

5.1.1 Fertility

The population explosion continues. People are living longer and around 1.8 billion women are now in childbearing years. The global population will keep growing for another few decades at least, even though each woman is having fewer children than she would have had a generation ago. With the

> population still growing by about 80 million a year

it is hard not to be alarmed. Right now, water tables are falling, soil is eroding, glaciers are melting and fish stocks are vanishing. Close to a billion people go hungry each day. A few decades from now there will be two billion more mouths to feed, mostly in poor countries. In 18th century Europe or early 20th century Asia, when the average woman had six children, she was doing what it took to replace herself and her mate, because most of those children never reached adulthood. When child mortality declines couples eventually have fewer children, but that transition usually takes a generation at the very least. Today, in developed countries, an average of 2.1 births per woman would maintain a steady population. In the developing world the 'replacement fertility' is somewhat higher. In the time it takes for the birth-rate to settle into that new balance with the death rate, the population will still increase.

The fertility for 'steady state' population is around 2.1. Since the 1970s the population growth rate has fallen by more than 40%.

The fertility decline that is now sweeping the world started at different times in different countries. Globally it started in the 1970s. Since then the population growth rate has fallen by more than 40%. Though its population continues to grow, China is already below replacement fertility – and has been for nearly 20 years – thanks in partly to its coercive one-child policy, implemented in 1979. In most of the world the family size has shrunk dramatically. Still, south of the Sahara in Africa, fertility is still five children per woman. The UN projects that the world would reach replacement fertility by 2030. This is good news. The bad news is that the largest generation of adolescents in history will then be entering their childbearing years. Figure 5.1 depicts that the fertility rates are low in the high income world. In some countries the population trend is negative.

Figure 5.2 demonstrates that both extremes of fertility are represented in the world. Typically African countries still have very high fertility, while countries like India and Bangladesh have 2.8 children per women. UN reports a fertility rate of 1.7 for China. Remembering that this is an estimated average for a huge nation, some places have extremely few babies. Shanghai was reported to have 0.7 babies per woman in 2000, while Jiamusi close to the Russian border has 0.41 fertility, the lowest in the world. Russia's population decreases with more than half a million each year. According to the Russian Prime Minister Vladimir Putin (in 2011) 'this is the most acute problem facing our country today'. On Monday 13 Februari 2012 Mr. Putin vowed to reverse Russia's demographic decline and boost its population to 154 million (an increase of 11 million), as he ramped up his re-election campaign (The Telegraph, UK, 14 February, 2012).

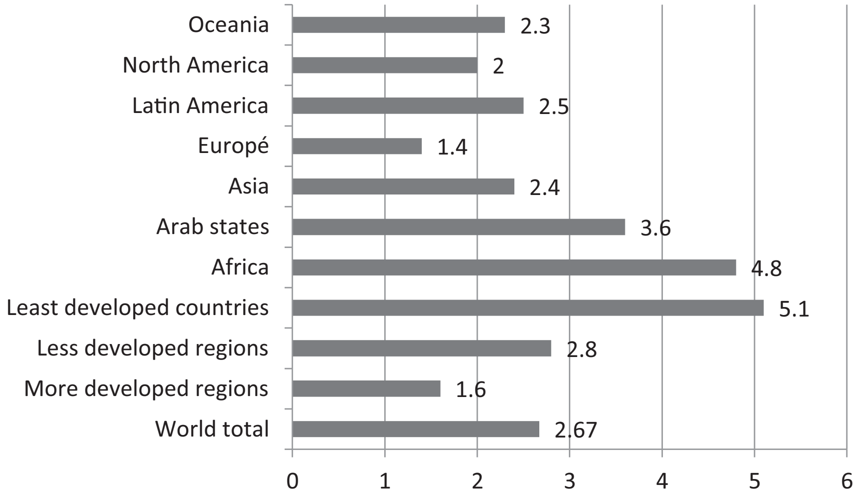


Figure 5.1 The fertility rates in 2005–2010 in different parts of the world. (*Source*: UN DESA (2012).)

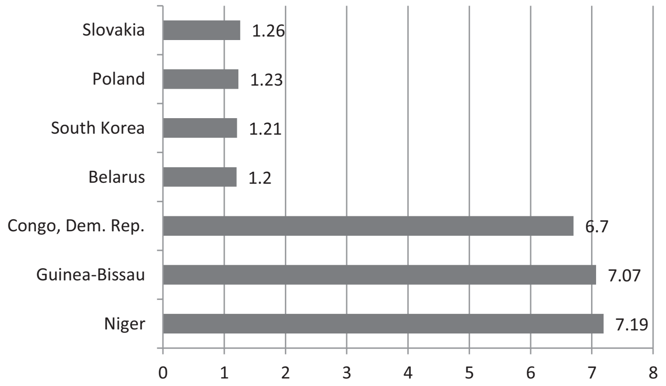


Figure 5.2 Countries with lowest and highest fertility rates 2005–2010. (*Source*: UN DESA (2012).)

Absolute numbers may be more illustrative than percentages. In 1987 the number of additional people in one year peaked, 87 million. In 2011 there were still 78 million people added to the world population in one year. The population increase is projected to fall steadily to about 41 million per annum in 2050.

In 2013 the world got 1.5 million new people, every week.

5.1.2 Population and natural resources

The demand for natural resources will be stressed by both rising prosperity and the sheer number of people. It is widely recognized that the consumption of resources now enjoyed in the wealthiest nations will be impossible to sustain worldwide. Human beings now are living off natural capital, eroding soil and depleting groundwater faster than they can be replenished. This will soon be cramping food production. A most controversial consequence of the population increase is the rising tide of migration. One reason is the obscene income differences around the world. Since some countries have more than six children per woman and others barely more than one the migration becomes a safety valve for both sides. Europe, North America and East Asia already need foreign workers to keep the societies functioning, even if we pretend the opposite is often believed.

IPCC has reminded that the climate change is not only due to the population increase. Carbon emission from fossil fuels is growing fastest in China, thanks to its prolonged economic boom, but fertility is already below people replacement (the milestone of 7 billion people on earth would have happened five years earlier had it not been for China's family planning policy). On the other hand, the population is growing fastest in Sub-Saharan Africa. Emission per person is only a few percent of what they are in the USA. Therefore population control in these African countries would have little effect on the climate.

Emission depends not only of the number of people but on the consumption patterns.

The number of people does matter, of course, but how people consume resources matters a lot more. It is time for all of us to change how we produce and consume food and energy. Eating less meat may be more reasonable that having fewer children.

5.2 URBANISATION

Rapidly increasing urbanisation is one of the most distinctive changes of the 20th and early 21st centuries. All over the world people are moving away from rural areas towards the cities. Today there are more people in urban areas than in rural areas in the world, Figure 5.3. In many cases, this migration is triggered by poverty resulting from large scale destruction of natural resources for example deforestation, overgrazing and resulting erosion problems. The challenge of urban and peri-urban areas is the unpredictability and the rate of migration, which makes it difficult to plan and ensure appropriate water services. Again, flexible and innovative solutions are needed to cope with sudden and substantial changes in water demand for people and their associated economic activities.

During the last 40 years the urbanisation has increased rapidly and the growth seems to increase. For the developing world it is expected that 56% will live in cities in 2030 and during these two decades there will be required some 1,500,000 km^2 more urban areas. This corresponds to the combined areas of France, Spain and Germany. According to IPCC the land-use change on this scale may significantly contribute to changing the local, regional or even global climate and has an important impact on the carbon cycle. In contrast, the urban population of the more developed regions is expected to increase very slowly, from about 0.9 billion in 2005 to 1 billion in 2030, an annual growth rate of about 0.5%. The more developed countries were 74% urban in 2005 and this is expected to increase to 81% in 2030. It is anticipated that the rural population in the developing countries will reach its peak of 3.1 billion people in 2020 and will then start to decline slowly.

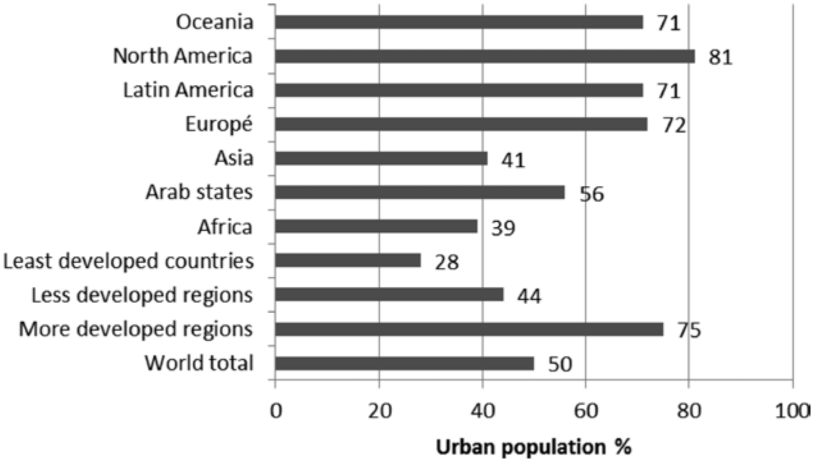


Figure 5.3 The urban population in different parts of the world. (*Source*: UN DESA (2012).)

5.2.1 Food and water

The migration also raises issues about safe food supply and its associated water requirements, due both to the concentration and increase of demand, and to the competition for land in peri-urban areas where urbanisation pressure pushes away agriculture, even from areas with high agronomical potential. On the other hand, safe re-use of water by peri-urban agriculture could be of great interest. Turf and landscape irrigation is a very high water consumer and is also able to re-use treated wastewater. In densely populated areas there are additional risks of accidental and deliberate pollution of water resources. Consumers in urban areas tend to be more critical and well informed and expect a safer and higher quality of service. This requires increased security and monitoring as well as emergency systems.

Urban areas around the world suffer from old and deteriorating water infrastructures that are very vulnerable to failure due to aging, damage from excavations or over-loading. While existing water reuse options have to be further developed and implemented, the need for smaller scale, adaptable, local infrastructure systems is immense. Measures have to be taken to ensure the needed public acceptance of such innovative solutions.

In addition to the population increase, the way we use the land is changing rapidly. By using land resources people seek to develop a better way of life. Land is converted for agricultural use or for industrial and urban uses. This often requires more water or results in the degradation of water quality. The choice of energy sources – coal, oil, nuclear power, biomass, biofuels – all have significant implications for both greenhouse gas emissions and for water.

5.2.2 Rural and under-developed areas

Many rural and under developed areas lack any significant infrastructure for water services. Frequently, wastewater and agriculture water management have an adverse impact on water quality in small settlements without people being even aware of these hazards. Not only the poorest countries face this problem, but also some European countries. It is estimated that more than 10% of the European population receives water from small supplies that do not meet European drinking water standards. Most of these people are self-supporting and involved in small scale agricultural activity, since industrial activity is limited. The lack of basic infrastructure makes these areas less attractive for economic activity and development. Municipalities and regional or national governments often lack the money and the know-how to initiate the needed development.

Water supplies, wastewater treatment and reuse for public, industrial and agricultural water needs in such remote areas need to be non-conventional, decentralised, easy to service and highly reliable. The technology needed must be affordable and manageable. Improvement of the water infrastructure may attract new developments in such regions and help to reduce migration to urban areas. Once such new technologies have been implemented and proven, they may have attractive export potential to developing countries.

5.3 CHAPTER SUMMARY

The population development, increasing urbanization, rising incomes, and climate change will have impact on water, energy, food and land use. We will first turn our attention to the need for food and land use (Chapter 6). It becomes so obvious that all the issues of food, land use, water and energy cannot be solved in isolation, but integration is crucial (Chapter 7). Part of the problem is how we value the water and how this is reflected in the price we pay (Chapter 8).

More energy will require more water and more water use will require more energy supplies. Part III of the book is devoted to the water need for energy extraction and production. Part IV discusses the energy need for all the water operations.

5.4 MORE TO READ

There is a wide spectrum of literature on the population development. UNDP and FAO are primary information sources. Pearce (2011) presents a brilliant discussion on the population development. In the January 2011 issue of National Geographic a lot of space is devoted to the population development. Professor Hans Rosling, professor of International Health, Karolinska Institutet, Stockholm, Sweden, has studied the population issues for many years. His TED Talks at Youtube are not only extremely informative but also so exciting (look for 'Hans Rosling' at youtube.come).

6

Food, water, energy and land use

> *The real crisis is not oil – it is all about water.*
> Mikhail Gorbachev, the last Soviet Union President

Food, water and energy form some of the basic elements of sustainability considerations. As noted in Chapter 3.3 food production depends crucially on both water and energy. Decisions regarding energy and bio-resource consumption and procurement have an impact not only on the countries or regions where they are made, but on the world in general. This book will not explore the relationship between food, water and energy in detail. However, it is important to keep in mind that the agricultural needs will influence the water resources to a large extent.

> Agriculture, including forestry, livestock and land use changes, account for over 30% of the global GHG emissions.

Some 70% of water withdrawals are used globally for the food production, and 11% of the world's land is used. The food sector currently accounts for 30% of total end-use energy consumption (FAO, 2013). Therefore agriculture needs to be carefully considered not only for water resources but also for future carbon market mechanisms. For example, agriculture and land use changes in Brazil account for about 70% of the GHG emissions (2010) in the country. China, on the other hand, is now a net carbon 'sequesterer' from land use changes. Agriculture in China contributes with about 15% of all GHG emissions (2010). The country has had a long term program of watershed and agricultural landscape restoration.

6.1 OUR NEED FOR FOOD

The real danger to our planet is probably not the emissions from smokestacks and cars but our need for food. Climate change is an agonizing threat to the food supply for the world. Year-to-year climate variability has a large influence on agriculture, which is heavily dependent on rainfall, sunshine and temperature. Human induced climate change has introduced a new complicating factor into the food security equation which is changing this climate variability. At higher latitudes some producers may benefit from a longer growing season. But arid and semi-arid areas will experience increased water stress.

To understand how climate change can alter food production also requires an understanding of how the changing agriculture sector affects socioeconomic conditions, from food prices to consumption patterns, and how these in turn affect food production. Only a thorough systems analysis can provide this kind of understanding. The IPCC expresses with 'high confidence' (IPCC, 2014a, pp. 10, 17) that 'based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts'. Global warming has the potential to boost food production in some parts of the world (such as Canada and Russia) and limit it in others (such as southern Africa).

There is expected to be an increase in the frequency and intensity of extreme events such as floods and droughts, which will have an impact on crops and livestock, as discussed in Chapter 4.

The food production has increased enormously during the last 50 years. The Green Revolution led to a near-tripling of the global grain harvest through a combination of high-yielding seed varieties, fertilizer, and a doubling of world irrigated area. By boosting the productivity of cropland, it spared substantial natural areas from being plowed. Some of the good news are:

- Per capita consumption of food and total consumption of fruits, vegetables and livestock products are steadily rising.
- The average global per capita daily food supply increased from 2400 kcal in 1970 to 2800 kcal in 2000, despite the population growth.
- The food productivity increased steadily over the last 40 years, from 1.4 metric tons per hectare to 2.7 metric tons.
- In some areas environmental degradation has been reduced because of better natural resources management.

The price has been paid with water. With 70% of all freshwater being used for irrigation many water supplies are drying up. Agricultural water use exceeds excessively long-term environmental sustainability levels.

As the Earth's population grows, only dramatic improvements to every link in the human food chain have to be realized to meet the global demand. Despite the land and water constraints, farmers will need to grow enough food to feed millions of additional people over the next decades. Some of the disturbing facts are:

- Still some 850 million people remain malnourished;
- The average daily per capita food supply in South Asia (2400 kcal) and Sub-Saharan Africa (2200 kcal), while slowly rising, remained below the world average of 2800 kcal in 2000. It is far below the excessively high level in industrial countries (3450 kcal);
- The loss of food between what is supplied and what is consumed (of the order 35%) is also a waste of both water and energy.

The food issue depends on the environment in more than one way. Uganda can serve as an illustrative example. The National Environmental Authority estimates that at the present rate of deforestation the country is likely to be importing firewood by 2020. Some 80% of Ugandans depend on firewood for fuel. So,

> even if the food were to be found in the years to come, in many African countries ravaged by environment degradation, the difficulty might be the energy to cook it.

Increasing water withdrawals and water depletion for irrigation in developing countries have been good for economic growth and poverty alleviation – but often bad for the environment. Agricultural subsidies (including energy subsidies) can be beneficial if applied judiciously. If not, they distort best water and agricultural practices.

6.2 WATER FOR AGRICULTURE

The world population withdraws 8% of the annual renewable freshwater and withdraws 54% of accessible runoff. Humans are responsible for about a quarter of the annual evapotranspiration. Most of the freshwater use in the world is in agriculture and industry, Figure 6.1.

> Agriculture takes 70% and at least half of that water is lost to evaporation or runoff.

Globally, 80% of water for agriculture comes directly from rain on non-arid areas, and about 20% comes from irrigation on arid areas. Industry consumes the remaining 20–22% of water, often inefficiently. Only 8–10% of the water consumed worldwide is for household use.

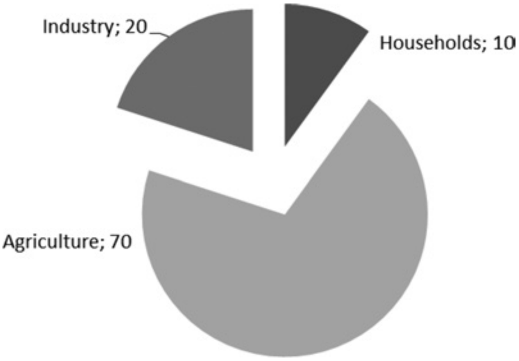


Figure 6.1 The global water demand. (*Source*: World Almanac (2011).)

Farming for food and bioenergy is the thirstiest user of our water supplies and a major polluter, as runoff from fertilizers and manure disrupts fragile lakes, rivers and coastal ecosystems across the globe. Agriculture also accelerates the loss of biodiversity and actually agriculture has become a major driver of wildlife extinction. This happens when grassland and forests are cleared for farms. Actually an area roughly the size of South America has already been cleared to grow crops. This includes the prairies of North America and the Atlantic forest of Brazil. Avoiding further deforestation should be a top priority. The farmland that replaces tropical forests seldom benefits the 850 million people that are most hungry. Mostly this land is used to produce cattle, soybeans for livestock, timber and palm oil.

Reusing water and adopting other conservation measures could help the world's industry cut its water demands by more than half.

The annual global freshwater withdrawals are estimated at 3,800 km^3. Out of this around 2,700 km^3 are used for irrigation, with huge variations across and within countries. This means close to 1 m^3 per person per day. To produce enough food to satisfy a person's daily dietary needs takes about 3 m^3 of water converted from liquid to vapour – about 1 liter per calorie. Rain provides the water for food production in the countries with less scarcity. Only 2–5 liters of water are required for drinking. But, the amount of water per person can be reduced by changing what people consume and how they use water to produce food (see further Section 6.2). The 3 m^3 per person per day is translated to 7,700 km^3 of water that is needed to produce the food for the 7 billion people during one year. This volume corresponds to an imagined canal 10 m deep, 100 m wide and 7.7 million km long – long enough to encircle the globe more than 190 times.

The variations are of course large between different regions, Figure 6.2. In high-income countries, 59% of freshwater is used by industry, whereas only 10% is used in industry in low and middle-income countries.

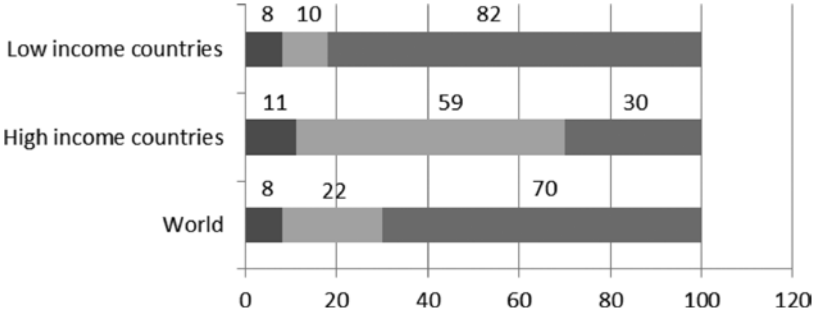


Figure 6.2 Water uses in different parts of the world. From left to right: domestic, industry and argriculture uses. (*Source*: WWAP (2011).)

Looking at the specific water consumption at the different continents more than 60% of all water is withdrawn in Asia, more than 10% are withdrawn by Europe and North America respectively, and around 5% is withdrawn by Latin America and the Caribbean, and even less in Africa. Figure 6.3 shows the annual water withdrawal per capita in different regions of the world.

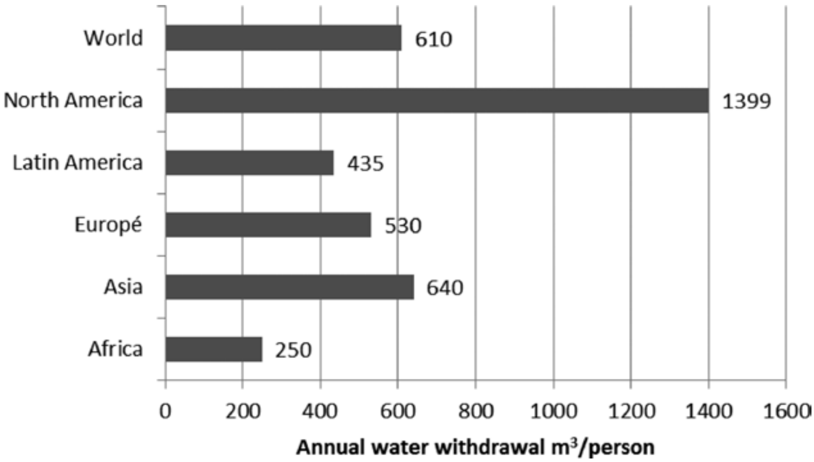


Figure 6.3 Total annual water withdrawal per person at the different continents. (*Source*: WEC (2010a).)

It is obvious that most water is used for agriculture in less developed areas. This is also reflected in the water use for agriculture at the different continents, Figure 6.4. Irrigation varies in different regions from the highly mechanized to methods that have been used for centuries.

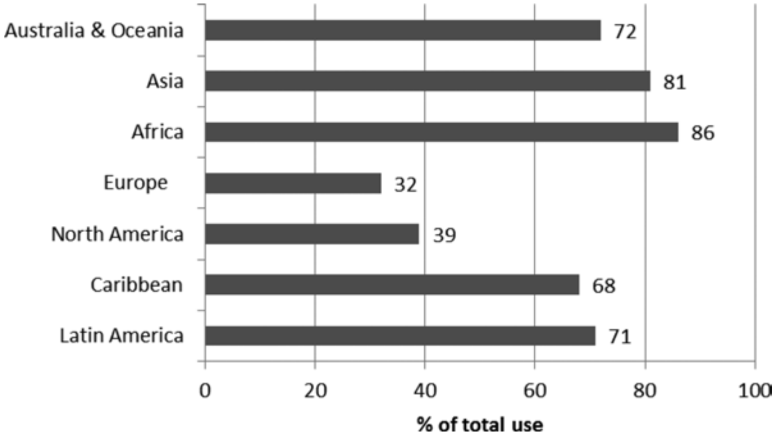


Figure 6.4 Water use in agriculture, in percent of total use. (*Source*: FAO (2010).)

The demand for freshwater is increasing, with some sources predicting a gap of 40% between demand and supply within as little as 20 years. Several estimates indicate that by 2030 farmers will need 45% more water than they use today. And, as remarked, the agriculture already uses 70% of the water (World Bank, 2011a; FAO, 2010; Worldwatch Institute, 2011, 2012, 2013, 2014; WEC, 2010a).

The demands of farmers have increased and the supplies of rain and surface water have not been enough. Groundwater has been the solution. In many places the withdrawal from groundwater far exceeds the recharge. This is true in the USA as well as in India, Northern China, North Africa and the Arabian Peninsula (Siebert *et al.* 2010). Collectively the annual water depletion in these countries is around 160 km^3, which corresponds to the total annual flow of two Nile Rivers. This situation has become very serious not only in the countryside, but many large cities depend on aquifers for their drinking water. Mexico City with its 20 million inhabitants draws some 70% of its water from an aquifer that will run dry, at current extraction rates, within 200 years. Similar challenges are seen in Bangkok, Buenos Aires, Beijing, and Jakarta.

Groundwater is used for agriculture in a non-sustainable way in many places. Pumping energy consumption is significant.

The Asian Development Bank estimates (ADB, 2013b) that with the total annual sustainable freshwater supply remaining static at 4,200 km^3, the annual deficit for 2030 is forecasted to be almost 2,800 km^3, or 40% of unconstrained demand, assuming that present trends continue. India and China are forecasted to have a combined shortfall of 1,000 km^3 – reflecting shortfalls of 50% and 25%, respectively. There is little evidence of changing trends. Signals of scarcity and stress have had little impact on policies, demand, or the market.

On the supply side in Asia ADB expresses that there is little room for finding and abstracting more water. In areas with physical water scarcity (such as Northern China, South and Northwest India, and Pakistan), demand needs to lessen. Elsewhere in Asia, with economic water scarcity (Bangladesh, Cambodia, North and Northeast India, Lao People's

Democratic Republic, Myanmar, Nepal, and Viet Nam), new investment may still be aimed at improving supply-side infrastructure.

However, solutions have to be found mainly on the demand-side. It is recognized by several international organizations that as much as 50% of the water for agriculture may be used more productively, for example through elimination of irrigation or production inefficiencies. In particular, in South Asia, irrigation efficiencies have been allowed to remain low through energy subsidies, although there are encouraging signs with the uptake of new technology. Water efficiencies in agriculture increased by only about 1% per year between 1990 and 2004 (ADB, 2013b). Of the food produced, up to 40% is often wasted.

6.2.1 Irrigation practices

In his book East of Eden (1952) John Steinbeck wrote: 'and it never failed that during the dry years the people forgot about the rich years, and during the wet years they lost all memory of the dry years.'

Poor drainage and irrigation practices have led to waterlogging and salinization of around 10% of the world's irrigated lands, which corresponds to around 300,000 km^2. A combination of salinization and waterlogging has degraded another 800,000 km^2. This land area is larger than France and Spain combined. Furthermore, agriculture is responsible for most of the depletion of groundwater along with up to 70% of the groundwater pollution. Both are accelerating.

There is a reckless management of water and soil in many countries today.

> In the United States, close to 19% of farm energy use is for pumping water. In some states in India where water tables are falling, over half of all electricity is used to pump water from wells. In India, at an average, more than 30% of electrical power is used for irrigation, industry and household water production. In Sweden it is around 0.5%.

To flood the fields to irrigate crops will waste most of the water.

If the conventional irrigation could be replaced by simple drip irrigation systems the agricultural demand for water could be cut to half. Wealthier people can invest in more efficient irrigation. In drip irrigation the water is supplied as drops in pipes close to the crop roots. This is a simple technology that could secure the life of millions of people. Drip irrigation uses 30–70% less water than traditional methods and increases crop yields. The first drip systems were developed in the 1960s, but even now they are used on less than 1% of irrigated land. The drip irrigation gives the plants 'what they need every day.' Typically, one farm in South Africa managed to quadruple the production of fruit per hectare while using only one third of the water. Most governments subsidize irrigation water so heavily that farmers have little incentive to invest in drip systems or other water saving methods (pricing and tariffs is further discussed in Chapter 8).

In a couple of high-income countries, Australia and California, the strategies to deal with the droughts have been quite different. Both regions depend on complex pipe systems to move the water. Australia's drought response in the early years of this century was to reduce urban water use by investing billions of dollars in conservation, education and efficiency improvements. And more important, Australia began to reform the old water allocation system, which, like California's, had promised specific amounts of water to rights holders. Australia instituted a system that guaranteed a minimum supply for the environment and then divided the rest into shares that could be sold and traded or stored for the next season. So far some California regional authorities have instituted rules to protect groundwater supplies. Los Angeles and other large cities have dramatically improved water efficiency.

6.3 THE WATER FOOTPRINT AND VIRTUAL WATER

A huge amount of water is captured in the food that cattle, poultry and we eat. This water is called virtual water and will be described below. We also talk about water footprint. This is an indicator of water use that looks at both direct and indirect water use in consumption or production. It is defined as the total volume of freshwater that is used to produce goods and services and consumed by individuals or communities.

6.3.1 Virtual water

The concept of virtual water was invented in 1993 by the British economist Professor John A. Allan from King's College in London (in 2008 he was awarded the Stockholm Water Price), see Hoekstra (2003). The virtual water concept measures how water is embedded in the production and trade of food and consumer products. It gives a dramatic illustration and explanation of the water crisis. The water requirement for various food products has been published in many places and we can just remind about some of the virtual water content in common food products, Figure 6.5.

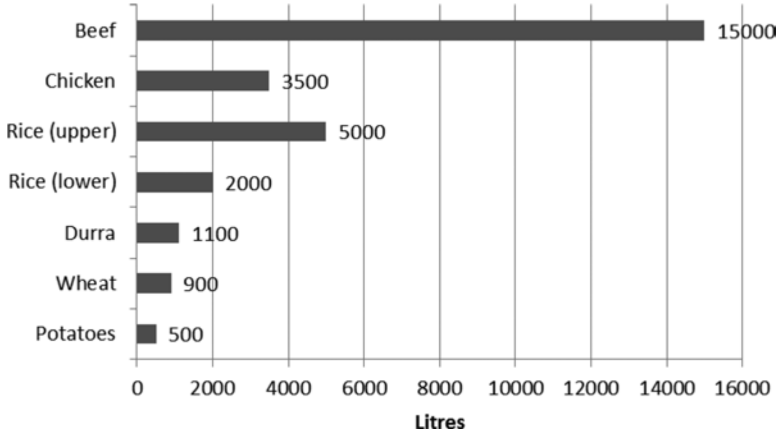


Figure 6.5 The virtual water content in 1 kg of some common food products. (*Source*: Water footprint network, www.waterfootprint.org.)

What makes the situation even worse is that a water rich region, such as Europe, is a net importer of virtual water from regions with severe water scarcity. Also Asia and Australia are net importers, while North and South America as well as Africa are net exporters of virtual water. Regions leading in beef and grain exports are the top exporters of virtual water. Japan imports 15 times more virtual water than it exports, the highest disparity for any country. Italy has Europe's largest virtual water trade deficit, and imports exceed exports by 49 km^3. The average consumption of virtual water is about 6,800 liters per day per person in the US, which is three times the amount for the average Chinese. In Sweden we use at an average 5,900 liters per person and day. The average global consumption is 4,300 liters.

'Wet' countries are often net importers of virtual water from countries with water scarcity.

An increase in global trade in food products and in consequent flows of virtual water has two sides: one is the prospect for better national food security; another one is the possibility of either increasing water stress or relieving water stress. The carbon emission caused by this trade is significant.

6.3.2 Water footprint

The urgent need to reduce the water footprint is starting to get recognized. This concept was coined by Professor Arjen Y. Hoekstra, University of Twente, The Netherlands. The website www.waterfootprint.org is an important source of information for the water footprint and also contains a water footprint calculator. The research group has produced the water footprint manual (Hoekstra *et al.* 2011) that sets the standard for calculations.

Some 85% of the global water footprint is related to our food. Generally animal products use much more water per calorific value than crops.

> The consequence is that if we are serious about decreasing our footprint we have to look at the diet rather than the water use in the kitchen, bathroom or garden.

The increased wealth has spurred people's appetites, boosting the demand for luxury foods such as seafood and beef. The oceans are getting emptied of fish; all but 10% of the large fish in the seas have been plundered. Rain forests are getting cleared not only for cattle but also for soybeans and oil palms planted to make biofuel to replace fossil fuels. And the petroleum could power the fishing vessels to reach every corner of the oceans.

A water footprint can be described by three components. The blue water footprint is the volume of fresh water that is extracted from rivers, lakes and groundwater. The green water footprint is the volume of water obtained from rainwater stored in the soil. In connection with water reuse we can also talk about grey water footprint.

The impact of the water footprint of animal products as compared to crop production depends on the water availability and the alternative uses of the land. In an industrial food production system the water used to grow feed for the animals may be far from where the animal is raised. On the other hand, the water footprint of beef from a grazing system is mostly related to green water. If the pastures are such that they cannot be used to grow crops, then the water could not have been used for crop cultivation. However, if the pasture can be used as a cropland the green water used for the animal production is no longer available for crop production. Therefore it is important to consider both water availability and alternative uses of the water.

Globally 60 billion farm animals are used for food production every year. It is well accepted that methane emissions from cattle and other livestock are major contributors to greenhouse gas levels and to climate change.

> Livestock generate as much as 18% of all human-caused greenhouse gases.

The global meat consumption has increased from 139 million (metric) tons in 1983 to 184 in 1993 and projected to 303 million tons in 2020. That means more than a doubling in less than 40 years (The International Food Policy Research Institute, IFPRI). The FAO predicts that meat and milk consumption will double by 2050, potentially raising the number of farm animals used annually to close to 120 billion. What will this mean for the health and well-being of those animals, of the people who consume ever larger quantities of animal products, and for the health of the planet itself? The large amount of waste that pigs and mass-produced poultry generate both will pollute water sources.

Meat and milk production may double by 2050. What does it mean for water, pollution, and our health?

Animals are often fed with a variety of feed ingredients and feed supply chains are difficult to trace. For the individual customer it is almost impossible to estimate how any individual product has affected the world's scarce freshwater resources. Only if we buy milk, cheese, eggs or meat from an animal that was raised and grazed locally we may get some transparency. Our food system is getting increasingly complex. In particular animal products basically hide the links between the food in the store and its water and carbon footprints. It is quite apparent that the transparency has to increase if we are going to contribute to a smaller water footprint.

The increasing demand for water is caused not only by the growing number of mouths to be fed. People have a desire to better tasting and more interesting food. To grow a kilo of peanuts requires twice as much water as soya beans. It takes four times as much water to produce one kilo of beef as one kilo of chicken and five times as much to produce orange juice compared to the same amount of tea.

The food crisis is caused not only by the number of people, but also by the desire to better and more food.

The demand for more meat, eggs and dairy will create a pressure to grow more corn and soybeans to feed more cattle, pigs and poultry. Taken together, the population growth and the richer diets will require that the food production has to double by 2050. There seems to be a polarized discussion between industrial-size farms and small size farms. The former usually achieve high yields using fertilizer and pesticides to grow huge fields on one crop. The latter tend to lag behind the industrial farms in yields, but they often deliver more food that actually ends up feeding people. Probably we will need both types of agriculture also for the future to feed the world.

Figure 6.6 shows how big part of the calories that are used for feed to cattle or to biofuel. In the US, some 40% of the corn is used for biofuel. In Brazil more than half the soybean crops becomes animal feed and ethanol from sugarcane is the largest production in the world. In Africa most of the farms are small and the crop is mostly for human consumption. The same is true in India and in other parts of Asia. China feeds 77% of its corn to animals while humans consume 82% of the rice-crop calories.

Despite the rise of economies like in China the increase in consumption is still in the rich part of the world. The ecological footprint – proposed by Rees (1996, 1997) and

Wackernagel-Rees (1996) – in different parts of the world can be illustrated in Figure 6.7. The richest 1 billion people of the world (with some of them also in the developing countries) consume 32 times more than the average person of the remaining 6 billion people. This means that it is inappropriate to suggest that the food crisis is caused by the growing number of people in the developing countries.

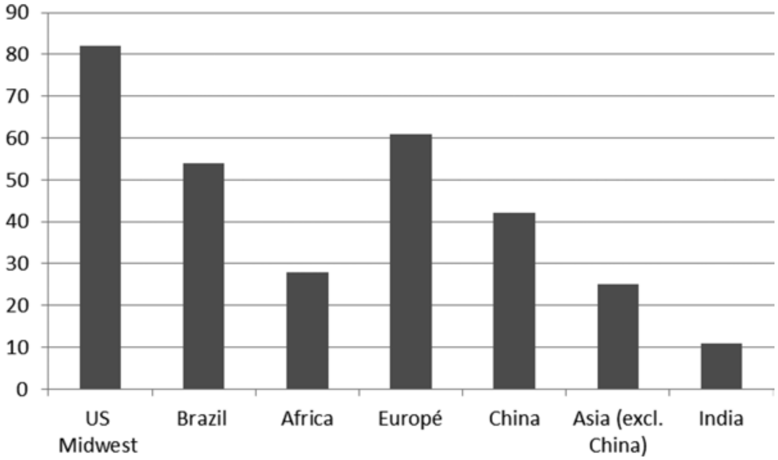


Figure 6.6 Percentage of the crop production used for cattle feeding or biofuel.

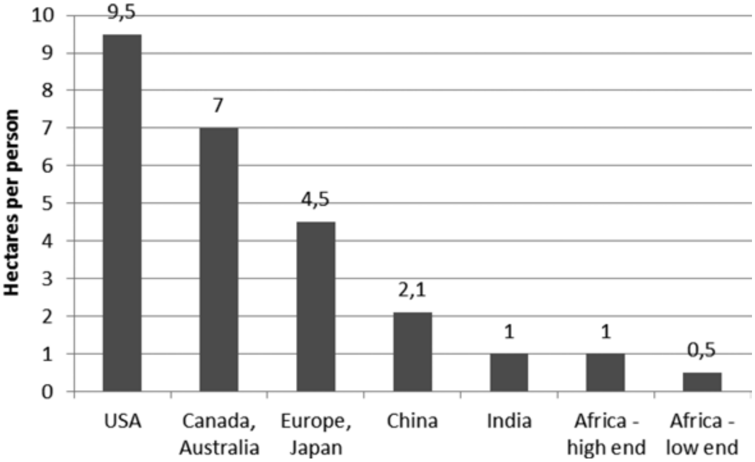


Figure 6.7 Ecological footprint in various regions of the world, measured in hectares per person. (*Source*: Wikipedia.)

The world-average ecological footprint in 2007 was 2.7 'global hectares' per person (18.0 billion in total). With a world-average biocapacity of 1.8 global hectares per person (12 billion in total), this leads to an ecological deficit of 0.9 global hectares per person (6 billion in total).

The average ecological footprint of the richest 1 billion are 32 times the average of the remaining 6 billion.

Of course the number of people counts. However, almost surely the consumption is a greater threat than the rising population. So, if consumption – including the use of water resources – is the main threat then we in the rich parts of the world have a serious responsibility. Surely, the efficiencies of our production, our cars, our housing and so on, have improved, but the problem is that the consumption has increased more than the efficiency.

6.4 ENERGY FOR AGRICULTURE

The development of modern agriculture is closely related to the increased use of energy. The very reason for agriculture's existence is to supply energy to mankind in the form of food and feed. Solar insolation and other power sources are converted into the biomass. Energy is used in the production and delivery of food, for pumping irrigation water, and for its transport, distribution, and cooling for storage. The cost and availability of energy in rural areas has had – and will continue to have – a decisive influence on the development of agriculture.

6.4.1 Energy for irrigation

Irrigation will of course influence the groundwater resources. Since the irrigation is mostly done in dry or arid areas there is a large risk that the groundwater levels will be decreasing, since the groundwater will not recover as quickly as it is consumed. There are several cases of serious water depletion and we illustrate some of them from Asia and from the US.

In countries in South Asia and North China there has been a dramatic growth of irrigation using groundwater. The rapid applications of rural electrification, subsidized electricity, availability of cheap pumps, and local well-drilling have caused a tremendous increase of the number of tube wells for irrigation. For example, in India, about 21 million wells were drilled in the past 20 years (ADB, 2013b). The volume of groundwater abstracted in India increased from 10–20 km^3 before 1950 to 240–260 km^3 by 2000. All of this helped to lift millions out of poverty and hunger. However, this supply is not sustainable everywhere – and the link with energy is crucial. Groundwater tables in Gujarat, western India, close to Pakistan, have lowered by more than 170 m, and are dropping some 6 m/year. Soon the groundwater will be beyond economic reach for most farmers. There is a similar dilemma in parts of China. When subsidies are no longer politically sustainable, and when global electricity prices rise, farmers will receive a 'double hit'. Some irrigation and farming practices have to be changed.

In the US, after World War II, irrigation technology reached a level that allowed for faster exploitation of the Ogallala aquifer in the US (Map 2.5). The US Geological Survey has reported that by 2005, the most heavily exploited areas, accounting for almost a tenth of the entire region, had seen the water table drop between 15 m and more than 80 m beneath the surface reference. Farmers in some of the prime agricultural areas with the richest water deposits – in western Kansas, eastern Colorado, and the Oklahoma and Texas panhandles – have had to spend more and more money and fuel to bring water from greater and greater depths.

Flowing through the natural short grass vegetation of western Kansas, once-great rivers like the Arkansas are fed not just by surface streams but also by water tables that reach up and away from their streambed. Across much of the region, irrigation has drawn aquifers down so far that the flow of water has reversed; now moving down and out of rivers into the surrounding dry ground. Rivers are actually dropping underground, leaving only dusty beds visible for much of the year (see e.g., Pearce, 2006; Solomon, 2010; Wikipedia; Fishman, 2011).

The huge Ogallala aquifer has shrunk at an alarming rate.

In Kansas, a significant portion of the Ogallala's area has already shrunk below the threshold −9 to 15 m thick – that can support large-scale irrigation. Kansas lies downstream from Colorado and Nebraska, and has fought bitter water battles with both states in recent years. Those border regions in which struggles over water have been fiercest are precisely the regions being eyed for new ethanol plants and bigger plantings of thirsty corn.

Further south, the situation is even worse. The USDA has recorded water-table drops of 30 m in the Texas Panhandle, and by 2025, several counties at the southern fringe of the Ogallala in west Texas will have lost 50–60% of their water that's available for pumping. Agricultural economists at nearby Texas Tech. University predict that unless restrictions are put in place, farmers will most likely respond to water shortages (and high corn prices) by drilling more wells and depleting the water even faster than that. It looks like a mining economy wherever groundwater is the resource to be extracted. The ultimate result of such an economy is a ghost town.

6.4.2 Energy for fertilizers

N (nitrogen), P (phosphorus) and K (potassium) are the three primary nutrients of plants. N is an important component of proteins, and as such is an essential nutrient for plants. P is a key to energy transfers in plants and is also a component of nucleic acids and lipids. K has an important role in plant metabolism, such as photosynthesis, activation of enzymes, and osmoregulation (the regulation of the osmotic pressure of an organism's fluids; to keep the organism's fluids from becoming too diluted or too concentrated). The energy use for European agriculture is illustrated by the production of wheat. Around 50% of the energy requirement is for the production, transportation and application of nitrogen fertilizers.

The production energy includes the energy used for the extraction and transport of the fossil fuels to the N fertilizer, Table 6.1. Modern fertilizer factories are close to the theoretical minimum of energy consumption when producing ammonia, which is the first step in the production of N fertilizer. In the early 1900s it was required some 400 GJ/tonne of N and now the requirement is about 40. The transport energy is calculated for a transport of N fertilizer over a distance of 400 km by ship and truck (1 GJ = 25 liters of oil, see Appendix 2). Of course, the fertilizer production means a carbon footprint. The energy required to produce phosphorus fertilizer is around 10 kWh/kg P.

Table 6.1 Energy consumption in the N fertilizer chain.

Process	Energy use GJ/ton N	Energy use MWh/ton N
Production	40	11.1
Transport	1	0.28
Spreading	3	0.83

Source: European Fertilizer Manufacturers Association, www. efma.org.

> *Fertilizers require energy for production, which causes carbon emission. With proper processes there is a net gain in energy.*

Grain yield increases as more mineral N is applied. However, there is an economic optimum of N fertilizer rate at about 170 kg N/ha, resulting in a wheat yield of 8.2 tonnes per hectare (compared to 4.7 tonnes without N fertilizer). These 8.2 tonnes equate to 126 GJ (≅35 MWh) of solar energy captured in the form of biomass when nitrogen is applied compared with 71 GJ (≅19.7 MWh) without any N fertilizer. The extra 55 GJ (≅15.3 MWh) captured when using N fertilizers can be compared to the 8 GJ (≅2.2 MWh) used to produce, transport and spread the same fertilizers.

6.4.3 Improving water and energy use in agriculture

There is a huge amount of proposals how to improve the efficient of agriculture all over the world. Some major steps are indicated here (ADB, 2013b):

- *Improve existing irrigation systems*: encourage farmers to reduce groundwater use, since it is often more expensive than surface water supply of similar quality. Improving water use efficiency will also save energy, since the demand to pump, lift and transport water may be reduced.
- *Water storage capacity*: using reservoirs and catchments in wise way may improve the water use efficiency
- *Decrease the amount of fertilizers*: the energy embedded in inorganic fertilizers is significant. By saving fertilizers not only energy can be saved but also pollution can be decreased.
- Avoid food losses and waste

In the world there are some 300 million irrigated hectares (3 million km^2, which corresponds to about 1/3 of US or 1/3 of China) and the water pumps consume around 62 TWh/year (this corresponds to about half the Swedish electrical consumption). On top of this: energy is needed for the manufacturing and delivery of the irrigation equipment. Most of the energy for irrigation is used for groundwater pumping. As groundwater irrigation, in general, provides greater flexibility than other types in responding to fluctuating water demands, its relative importance is likely to increase.

The agricultural sector needs accurate, reliable and timely weather and climate information for daily decisions and long term planning. The Global Framework for Climate Services (www.wmo.int/gfcs) has been formed, supported by WMO to supply this kind of help, both in terms of Agro-Meteorological information systems (The Wide Area Monitoring Information System, WAMIS, http://wamis.meraka.org.za), the Regional Climate Outlook Forum (RCOF, http://www.wmo.int/pages/prog/wcp/wcasp/clips/outlooks/climate_forecasts.html) as well as organized education for many farmers.

6.5 BIOFUEL AND FOOD

An increasing part of agriculture products are used for biofuel. Increasing attempts to decrease emissions together with increasing oil prices have transformed the biofuel industry to become a global industry. 4% of the world's transportation is biofuel. In Brazil it accounts for 23%, in the US 5% and in the EU 4%.

An increasing part of the agriculture in poor countries is transformed to meet the demand from rich countries that try to decrease their carbon footprint. It is obvious that biofuel consumes crops that could be used to feed a hungry world. Actually, 99% of the biofuels produced and consumed worldwide in 2011 were made from food crops. The worldwide production of biofuel in 2011 was shared between the US (61%), Brazil (26%) and the rest of the world (13%).

From a water perspective, the most characteristic in feedstock production for biofuels is whether it takes place in rainfed or irrigated systems. In general, rainfed production of biomass does not substantially alter the water cycle. However, if bioenergy feedstock is produced on irrigated lands, then the potential impacts on groundwater and surface water resources can be a major concern, particularly when it comes to commercial feedstock production.

Biofuels not only use water for feedstock production, but also for processing. Water used in biofuel processing is a strong competitor for local uses, but after use it can be made available for other purposes. These return flows, however, often have negative impacts due to chemical and thermal pollution. The production process of biofuels also uses energy for mechanization, to produce fertilizers and to pump irrigation water. Overall, biofuel development needs to be considered in the context of land and water availability, energy needs and production, agricultural priorities and, especially in low income countries, rural development for poverty reduction and increased food security.

An increasing amount of research is spent on the so called second generation biofuel that – as opposed to corn or sugar canes – is not manufactured from food vegetables but from algae, municipal waste and different grass types. Cellulosic and algae based biofuels are not expected to compete with food, and will reduce land-use impact.

The relation between biofuel, water, energy and food is further analyzed and discussed in Chapter 12.

6.6 THE FOOD WE EAT AND THE FOOD WE WASTE

The real threat is food scarcity, the ever-present risk of food price instability and the still existing scourge of widespread poverty in the low-income countries, in particular in Asia and in Africa. A total of almost 850 million people in 2011–13, or around 1 in 8 people in the world, were estimated to be suffering from chronic hunger, regularly not getting enough food to conduct an active life (FAO, 2013). Agricultural productivity can be enhanced and food availability can be increased, especially when smallholders are targeted, and the hunger can be reduced even where poverty is widespread.

The National Geographic Magazine has devoted a series of issues in 2014 to the overarching question: how are we going to feed a growing global population?

We have to look for all kinds of answers, using water, energy and land more wisely in agriculture.

Earlier in history we could cut down forests or plow grasslands to make more farms. We have already cleared too much and caused the loss of whole ecosystems around the globe. Tropical forests continue to be cleared at an alarming rate. This is not a sustainable solution of the world population is going to survive. To trade rainforest for farmland is one of the most destructive things we do to the environment. Furthermore, this is done mostly to produce cattle, soybeans for livestock, timber and palm oil, not to feed the more than 800 million people in world that are still hungry.

The resources can be used more efficiently. In many parts of the world, particularly in Africa, Latin America and eastern Europe, improved farming practices would increase the yield of the food production. The green revolution (Section 6.1) relied on increasing use of water and fossil fuel-based chemicals. Over the last 50 years the area of land needed to feed one person has decreased from 0.45 hectare/person in 1965 to 0.22 hectare/person in 2008 (FAO, 2011). This has been achieved through the intensification of agriculture, which resulted in increasing use of water for irrigation and energy for fertilizers and machinery. Therefore, today we need to look at productivity not only from a land but also from a water and energy perspective. Today there are many examples of more efficient and skilled use of water, chemicals and machinery. Organic farming has a lot of promise.

6.6.1 Our diets

Today only 55% of the world's crop calories feed people directly. The rest are fed to livestock (some 36%) or developed into biofuels or other industrial products (some 9%). Figure 6.8 displays how many calories we will get from 100 calories of grain that we feed animals.

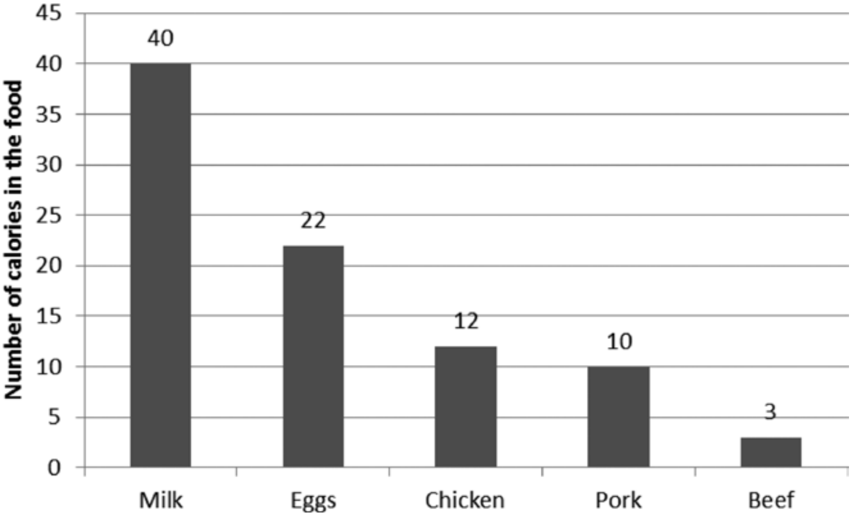


Figure 6.8 Given 100 calories of grain, fed to animals, the diagram shows the number of calories that are utilized when we eat. Data from National Geographic, May 2014.

Beef is a really expensive food, both from an energy point and from a water point of view (Figure 6.5). Shifting to less meat-intensive diets – or even shifting from grain-fed beef to chicken, pork or pasture-raised beef – could make so much more food available across the world.

Another cost of food is expressed in Figure 6.9. It is quite obvious that grain-fed beef is an extremely expensive and wasteful way to get proteins. Of course a growing food demand in the world cannot possible be met with meat.

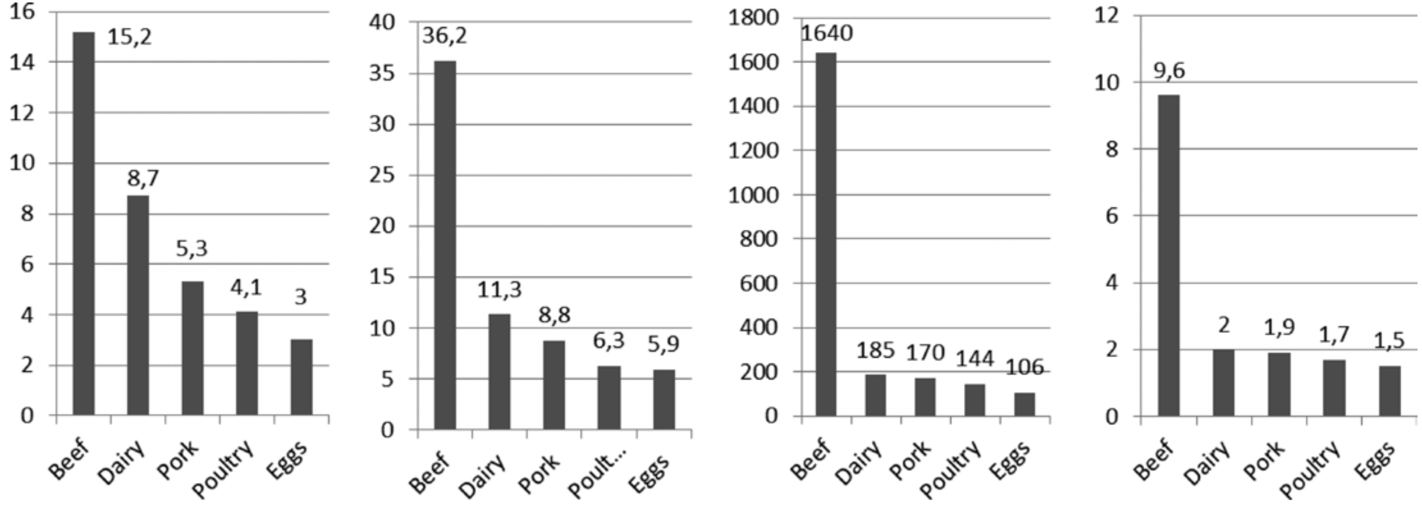


Figure 6.9 The production requirements to raise 1000 calories consumed by humans. (1) Land area in m^2, (2) average feed in thousands of calories, (3) average liters of irrigation water, (4) average kg CO_{2e} generated. Data from National Geographic, Nov. 2014.

This brings up a vital question about lifestyles: the real threat to the food supply is not the population increase, but the consumption patterns. There is enough grain to feed the 7 billion people in the world today.

An increasing amount of grain is used for meat production and for biofuel instead of being used directly.

6.6.2 Wasted food

Reducing food waste has an enormous potential.

Another crucial challenge is waste reduction. Consider this: according to FAO

> each one of us in the high income countries throw away about 100 kg of food every year.

Cuéllar-Webber (2010) have estimated the energy embedded in wasted food in the United States only. In 1995 around 27% of edible food was wasted. Their analysis shows that around 2000 trillion (10^{12}) BTU (≅600 TWh or ≅2 EJ) were embedded in wasted food in 2007. This corresponds to around 2% of the annual energy consumption in the US (which was 27,200 TWh in 2007 and 25,150 TWh in 2009) or 3% of the global *electrical* energy consumption. As a comparison, the *total* energy supply – including all losses – in Sweden was 616 TWh in 2010. The food waste is nothing less than a recipe for a food-energy-water disaster. In the developing world huge amounts of food are destroyed due to inadequate storage.

The energy embedded in the wasted food corresponds to some 2% of the total energy consumption in the USA

The global food waste is enormous: an estimated 25% of the world's food calories and up to 50% of total food weight are lost or wasted before they can be consumed. In rich countries most of that waste occurs in homes, restaurants or in supermarkets. In poor countries the quality of human food is often wasted between the farmer and the market, due to unreliable storage and transportation. Of all the options for boosting food availability tackling waste would be one of the most effective. Poor countries can improve crop storage and packaging. Rich countries can cut back on resource intensive foods like meat. In fact, wherever food is cheap there is a risk that we buy more than we consume. We could all start by shopping smarter – and filling less and emptying our plates.

The food vs. the transportation fuel issue is a conflict theme for the global community in view of the food-water-energy-land nexus. It is much more profitable to export the agricultural, high water footprint and high virtual water products like E85 fuel on the world market as high-energy-density commodities for the few rich than as low-energy and low-cost products for the many poor.

All of this requires a big shift in thinking. We actually know quite well what to do. But we have to do it! We have to be more thoughtful about what we put on our plates. We need to make connections between our food and the farmers who grow it, between our food and the land, watersheds and climate that sustain us. Much of this choice can be done in our rich countries as we walk along the aisles in the supermarket.

6.7 WOMEN AND WATER – THE GENDER ISSUE

The implications of fresh water shortages are also serious. Women head one-third of the world's families (in parts of Latin America families headed by women are the majority) and frequently are the financial mainstays of and principal water providers for their families. They are responsible for half of the world's food production, and produce between 60 and 80% of the food in most developing countries.

> *Women pay the highest price for water scarcity.*

To produce adequate sanitation and food they must first 'produce' water. As the principal water providers women and girls in developing countries spend up to 8 hours daily finding, collecting, storing and purifying water. This reduces significantly the time they might otherwise use for education, community involvement and cottage industries. If safe and reliable water sources do not exist nearby they are forced to pay exorbitant prices to street vendors or rely on unsafe local water resources. This has major implications for hygiene and the spread of diseases among poor women and their families. Finally, poor women's access to water is less than that of poor men because decisions are most likely made by men and the water needs of women are often ignored or undervalued. This has led to a situation where women are among the poorest of the poor in most parts of the world, leading to a 'feminization of poverty.'

> *We have to educate boys and girls worldwide, first on literacy, and then early with pedagogical tools like games on the water-energy-food-land nexus, and the causal links are halfway solved.*

6.8 FOOD PRICES AND FOOD PRODUCTION INDUSTRY

> *Money is no problem – the problem is no money.*
>
> T-shirt in Beijing

In 2008 FAO (the UN Food and Agriculture Organization) launched an 'Initiative on Soaring Food Prices', at a time when millions were driven back into hunger. The FAO also produced a 'Guide for Policy and Programmatic Actions' that urges total mobilisation for poor food-deficit countries to produce more. On 8 March, 2011 FAO issued a rare 'special alert' with the explanatory title: 'A severe winter drought in the North China Plain may put wheat production at risk'. Only five days before FAO reported that world food prices rose for the 8th consecutive month to their highest levels since it began keeping records in 1990. As described in Section 6.5, the production of biofuel is one significant factor that influences the food prices.

The drought in 2012 in China had great consequences for the food availability and food prices. In August 2012, FAO issued a rare 'special alert,' warning that the ongoing drought that has hit the provinces of Shandong, Henan, Hebei, Jiangsu and Shanxi – which together account for nearly two-thirds of China's wheat production – has already jeopardized crop yields and 'could become critical' if the dry spell stretches into spring. The state-run Xinhua newswire referred to the drought in Shandong as the worst in two centuries. In addition to concerns about China's crop, wheat prices were driven up by floods in Australia and a year-old ban on exports from Russia – normally one of the world's biggest producers and sellers – caused by a prolonged drought there.

As food prices have been rising, countries, large corporations and private investors have been buying land around the world. Few noticed when South Korea, China, Japan, Libya, Egypt, Persian Gulf countries and others acquired farmland in Laos, Cambodia, Burma, Mozambique, Uganda, Ethiopia, Brazil, Pakistan, Central Asia, Russia as well as in the US. The purchases weren't only about land, but also, if not mainly, about the water rights that belong to the land owner.

The global food prices are increasing.

Not until 2010 China imported any cereals. The wheat fields had dried up in what the Chinese media calls the most severe drought in 60 years in northern China. 'China's grain situation is critical to the rest of the world – if they are forced to go out on the market to procure adequate supplies for their population, it could send huge shock waves through the world's grain markets', said Robert S. Zeigler, director general of the International Rice Research Institute in the Philippines, according to New York Times. For decades, China had a self-sufficient policy and was guarding the farm output figures. China's grain situation is critical to the rest of the world, according to Robert S. Zeigler.

In a special report on 24 February, 2011, the Economist pronounced that 'an era of cheap food has come to an end'. 'A combination of factors – rising demand in India and China, a dietary shift away from cereals towards meat and vegetables, the increased use of maize as a fuel, and developments outside agriculture, such as the fall of the US dollar – have brought to a close a period starting in the early 1970s in which the real price of staple crops (rice, wheat and maize) fell year after year.'

The agriculture and food production industry employed more than 1 billion people in 2013 or 1/3 of the global workforce. The industry is huge, but it is dominated by a very small number of large corporations with an immense influence. Oxfam (2013) have described ten of the world's largest and most influential food and beverage companies. These corporations are so powerful that their policies – using advertising, food ingredients, environmental impact, and labor practicies – can have a major impact on our diets and working conditions, on millions of lives. They can dictate food choices, supplier conditions and consumer variety. The ten companies are among the largest corporations in the world. All of them had revenues in the tens of billions of US$ in 2013. Together they employ more than 1.5 million people and are contracted with far more.

Many of these companies and their brands are extremely well known. They often spend huge sums on advertising. Nine out of the ten companies were among the 100 largest media spenders in the world in 2012. Unilever media expenses in 2012 were US$7.4 billion, the second highest in the world. Coca-Cola spent more than US$3 billion.

6.9 CHAPTER SUMMARY

It is obvious that a growing population is a major factor behind the increasing food and water scarcity, but a main reason for these problems are lack of commitment and targeted investment, insufficient human capacity, ineffective institutions, and poor governance. The life style in our rich countries is strongly related to the problems in the poor countries.

- Agriculture uses around 70% of the world's freshwater;
- The demand is increasing, and it is estimated that the farmers will need 45% more water by 2030;
- Using too much groundwater for irrigation is not sustainable;
- Salinization is becoming a serious problem;
- The water footprint of food has to be recognized and should influence our eating habits;
- The virtual water trade is often in the 'wrong' direction, from dry countries to wet countries;
- The food and water crisis is not only caused by an increasing population, but also the individual consumption of food and water;
- Modern agriculture requires a lot of energy in terms on fertilizers. This also generates carbon emission;
- An increasing amount of grain is used for meat production and for biofuel;
- Water scarcity is closely related to poverty. Usually the women and children pay the highest prices;
- Food prices are rising. The poorest people will suffer most. The competition between biofuel and food has to be recognized;
- The waste of food is huge.

We now summarize the water-energy-food-land nexus in the next chapter before we devote the main part of the book to 'water for energy' and 'energy for water'.

6.10 MORE TO READ

National Geographic Magazine has devoted several issues to the global food problem; see National Geographic (2007b, 2010a, 2010b) and several issues in 2014, giving a really worthwhile account, easily readable for the layman. Several of the FAO reports are significant sources of information on the global food issues. D'Silva-Webster (2010) and Vogt *et al.* (2010) discuss in detail the water footprint of food production. Cribbs (2010) describes the global food shortage and what we can do about it. Youtube.com has a lot of material on 'food poverty'.

7

Global water resources

> *Have you visited the storehouse of the snow, or seen the arsenal where hail is stored, … Has the rain a father?*
>
> Job 38:22, 28

> *You ain't gonna miss your water until your wells run dry.*
>
> Bob Marley

In 2014 The World Economic Forum presented the Global Risk Survey (WEF, 2014). More than 700 leaders and decision-makers answered a survey. From a list of 31 risks, survey respondents were asked to identify the five they are most concerned about. The top risks in terms of impact were considered to be:

(1) Fiscal crises,
(2) climate change,
(3) water crises.

The available water resources have decreased dramatically over the last decades and in many places there are serious water crises. There are several contributing factors to this serious matter and we repeat the most apparent ones: the population explosion, the food production, the domestic, agricultural and industrial pollution, and climate change.

- Pollution is increasing and rivers are drying up.
- Freshwater fisheries have been damaged or are threatened.
- Land and water resources are being degraded through erosion, pollution, salinization, nutrient depletion and the intrusion of seawater.
- Several river basins are poorly managed. There is not enough water to meet all the demands.
- Groundwater levels are declining rapidly in densely populated areas, particularly in North Africa, North China, India and Mexico.

> Increased competition for water must generate new ways of looking at natural resources in a more integrated fashion than ever before.

We need to address the simultaneous management of energy and water by developing new systematic methodologies for targeting and design that minimize the requirements of energy and water at the same time.

7.1 CLIMATE CHANGE INFLUENCE

In Chapter 4, in particular in 4.1, we have described how the ongoing climate change contributes to worsen an already serious water crisis. Many dry areas are becoming even drier and glaciers are shrinking at an increasing rate, which seriously threatens the access to drinking water for millions of people. Not only humans but all living material need water for our survival. Therefore it seems that water demonstrates more clearly than anything else how everything is interrelated; the need of water for vegetation, animals and human beings. If the vegetation and the animals do not have sufficient water, then we cannot survive.

Climate change will affect the water supply in various parts of the world, but the more precise patterns are still uncertain. The future changes of the climate will make our old models of water supply obsolete. Maybe the most certain assumption of the future water supplies is that the future will not look like the past! We may not know what it will look like, but changes are coming. Already some of these changes are apparent. The most obvious threat by climate change is the increase in the evaporation losses and the increased water use as a result of higher temperatures.

Water supply models will have to change as a result of climate change.

The consequence of this is that planning for energy systems, urban areas and water infrastructures can no longer rely on established models. New phenomena have to be taken into consideration.

7.1.1 Feedback mechanisms between water and temperature

There are a lot of feedback mechanisms between temperature and water resources. When the temperature increases then more water is evaporated to water vapour. Since water vapour is a greenhouse gas the temperature increase will be increasing further. When snow and ice melt, then less solar radiation is reflected back into space. Instead the heat from the sun is absorbed in the ground or in the open sea, so that the heat is captured. One of the consequences is that the rate of global warming in the Arctic area is larger than in the rest of the world. These are positive feedbacks. There are also negative feedbacks. A strong and very basic negative feedback is radiative damping: an increase in temperature strongly increases the amount of emitted infrared radiation. This in turn limits and controls the temperature increase.

Even without changes in precipitation the water availability can decrease by 10% or more simply as a result of a temperature increase of 2–3°C. On top of this there may be increasing human demands. Future hydrology has to consider stochastic changes of the water supplies caused both by extended dry periods and increasing rains at other locations. The major difference is that climate is no longer stationary. As a result, future predictions have to handle a non-stationary climate. On top of that the stochastic variations will have increasing amplitudes, both positive and negative.

Water availability can decrease by 10% or more with a temperature increase of 2–3°C – without changes in precipitation taken into consideration.

An increasing evaporation will make already dry regions even drier. One example is the Sahel area south of Sahara. A dry soil leads to less formation of clouds and to more sunshine, which in turn increases the heat input. Also, since the evaporation is less for dry soil it also has less of a cooling effect.

The oceans are slowly getting warmer. This is probably the most contributing case to the fact that tropical storms have been stronger than the 20th century average during the last decade (Chapter 4.1).

7.1.2 Water and energy consequences

Climate change will affect supply of both energy and water. It is hard to predict the exact extent and rate of the impact, but the direction is quite clear and we should certainly make provisions and adapt to the forthcoming changes. Some of the water and energy related changes caused by climate change can be summarized as:

- *Melting glaciers and snow-packs*: there will be a loss of storage of water, a more unreliable water supply as well as more floods and droughts;
- *Intrusion of saline water due to the sea level rise*: problems with potable water and the need for treatment of brackish water;
- *Changed patterns of precipitation*: changes in rainfall, loss of wetlands in some areas and occurrence in others. Migration of habitat. Impact on hydroelectric generation capacity;
- *Increased frequency of 'natural' disasters*: more frequent occurrence of 'unusual' hurricanes, floods and droughts;
- *Heat waves*: higher temperatures, higher evapotranspiration, more evaporation from hydro dams, problems with cooling water for thermal power plants.

One of the most certain predictions of climate research is that global warming will make it rain more at higher latitudes during the winter. This is of course very harmful for life in the Arctic. It is expected that we will see more extreme weather conditions, and one of the primary consequences is water, either too much or too little. It is not a general knowledge how much extra latent heat can be carried by the hot air that is a result of global warming. The laws of physics tell us that for every 10°C increase in the air temperature the amount of water vapour that the air can hold doubles. This means that a 30°C air can hold four times as much 'hurricane fuel' as air at 10°C.

> *Warmer air can hold more water vapour – more hurricane fuel.*

Still we have too little knowledge about the character of the new nature of disturbances. One of the consequences is that the operations of many hydroelectric plants have to be adapted to new flow patterns, both to provide adequate water and electricity supplies in dry areas and to adequately protect dams and downstream areas in areas with greater risks for flooding. This challenge becomes even more complex in rivers shared by two or more countries or states. The risk for conflicts will be further amplified by the fact that water data are often classified and considered a national security issue. Regions dependent on hydroelectricity for a significant portion of their electrical power supply may suffer from decreasing dam levels that are caused by prolonged dry periods. This will of course influence both the economy and be a reason for conflict.

7.2 GROUNDWATER

Groundwater is a major source of water supply. This subsurface water is contained for most part in small cavities in rock and soil. One common way to obtain unpolluted groundwater is to dig deep wells that find ‘fossil’ water that has been at these levels for thousands of years. This source, however, is not renewable in any short time perspective. More shallow wells obtain their water from groundwater that recently was surface water and therefore subject to greater contamination.

> The luxury of fossil water is like oil reserves.

These reserves of water have been accumulated during centuries or millennia and stored underground. However, in many regions in the world we are quickly depleting those reserves to supplement over-allocated surface water supplies.

Most but not all bacterial contamination of water supplies stems from the use of surface water; rivers, lakes and reservoirs. Since surface water is often too contaminated it is tempting to use the fossil water, even if the energy cost is increasing. Even in a nation like the US this is a problem. A privately funded review of federal and state water tests by the Environmental Working Group (EWG, 2009) reported that the water supplies used by more than 14 million Americans contain agricultural pesticides in amounts that would be banned if these levels were found in food.

> *Deep groundwater is not replaced in the short term. Pumping energy is needed to extract it.*

In Figure 7.1 the groundwater pumping is illustrated from 8 out of the 15 countries with the largest estimated groundwater abstractions. Saudi Arabia has an overwhelmingly large consumption per capita. After that US and China are the large groundwater consumers, expressed in volume per capita.

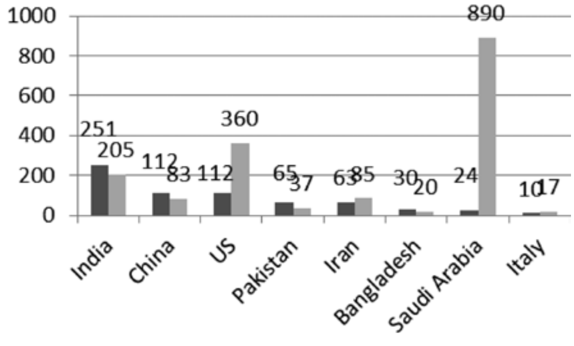


Figure 7.1 Annual groundwater abstractions (2010) in some countries. The countries are among the 15 nations with the largest estimated abstractions. The left bars indicate the estimated groundwater abstraction in 2010 (km^3/year) and the right ones the annual abstraction per capita (m^3/person/year). (*Source* The National Groundwater Association 2013, www.ngwa.org).

Not only rural areas depend on groundwater for irrigation. Major cities, like Beijing and Tianjin in China, Mexico City, and Bangkok in Thailand, are also becoming increasingly dependent on groundwater that is not replaced by rain.

The Worldwatch Institute (2014) estimates that by 2030, one-third of the world's population will live in regions where demand for water exceeds supply by more than 50%.

7.2.1 Groundwater use and misuse in some regions

Here we give examples from three different countries. Of course their use or misuse of groundwater is not unique. Some of the use and misuse of water for irrigation was described in 6.2.

> *In many places around the world groundwater levels are shrinking at an alarming rate.*

7.2.2 US

The Ogallala Aquifer (Chapter 6.4) is a hundred meter thick band of sandy material that lies below the Great Plains of the US, ranging from West Texas, Oklahoma and New Mexico in the south through Kansas, part of Colorado and Nebraska up to South Dakota (see Map 2.5).

In the 1930s just 600 wells tapped the aquifer. This had grown to 200,000 wells in the late 1970s. The U.S. Department of Agriculture has reported that in parts of Texas, Oklahoma and Kansas – three leading grain-producing states – the water table for the Ogallala aquifer has dropped by more than 30 m. Consequently, many wells have gone dry on thousands of farms. Huge volumes of water have already been pumped out of the aquifer and it is estimated that some 60% of the aquifer has already been consumed.

Groundwater depletion has been a concern in the Southwest and High Plains in the US for many years, but increased demands on groundwater resources have overstressed aquifers in many areas, not just in arid regions (USGS, 2014). Groundwater depletion occurs at scales ranging from a single well to aquifer systems underlying several states. Some examples:

- Groundwater pumping by Baton Rouge, Louisiana, increased more than tenfold between the 1930s and 1970, resulting in a decline of the groundwater of some 60 m.
- Houston, Texas has had a large economic and population growth. Extensive groundwater pumping resulted in water level declines of some 120 m. Extensive land-surfaces subsided up to 3 m.
- Memphis, Tennessee is one of the largest metropolitan areas in the world that relies exclusively on groundwater for municipal supply. Large withdrawals have caused regional water-level declines of up to 20 m.
- In Washington State and Oregon the Columbia River Basalt aquifer has been developed for groundwater irrigation, public-supply, and industrial uses. The water levels have declined more than 30 m in several areas.
- Increased groundwater pumping to support population growth in south-central Arizona (including the Tucson and Phoenix areas) has resulted in water-level declines of between 90 and 150 m in much of the area.

Chicago has been using groundwater since at least 1864 and groundwater has been the sole source of drinking water for about 8.2 million people in the Great Lakes watershed. This long-term pumping has brought down groundwater levels by as much as almost 300 m.

> One way to obtain more water is to buy farmland and the water rights that come with it. The apparent price is to take the farm out of production.

7.2.3 Saudi Arabia

Saudi Arabia has demonstrated how energy money can be wasted to get water in a most wasteful way. During the 1980s the government spent around US$40 billion to invest in pumping from an extremely large aquifer beneath the desert. A million hectares (10,000 km^2) were marked to be used for wheat farms. All the water was provided for free. Sprinklers were distributing water that had been pumped from 1000 m below ground. Of course a majority of the water evaporated. For every ton of wheat some 3000 m^3 of water was used, which is three times more than the global norm. The Economist (28 February, 2011) noted that this 'made about as much economic sense as planting bananas under glass in Alaska'. Today probably 60% of the water resources are gone.

7.2.4 India

The electric pump has powered India's green revolution as noted in Chapter 6.4. Surface irrigation projects have failed because of two reasons. One is that there is simply not enough water in the rivers. The other one is even worse: so much water is polluted that it cannot be used even for irrigation. So millions of farmers have taken things into their own hands and have bought cheap electric pumps and hired drilling equipment to find the groundwater.

The agricultural achievement has enabled the nation to grow enough food for its 1.2 billion people. This has been accomplished by a huge increase in groundwater pumping. In the mid 1950s fewer than 100,000 electric motorized pumps were extracting groundwater for Indian agriculture. Today about 20 million pumps are in operation, and the number is growing with about half a million each year.

India struggles to feed 17% of the world population with only 4% of the global freshwater resources. More than 85% of the nation's villages and over half of its cities rely on groundwater that has been extremely overused. Despite its water scarcity India is the largest freshwater user in the world (World Watch Institute, 2014). The unregulated use of so much groundwater has come with a high price. The aquifers have been depleted to the point that roughly half of India now faces over-pumping problems. According to an analysis by NASA hydrologists, India's water tables are declining at a rate of 0.3 m/year, and between 2002 and 2008 more than 108 km^3 of groundwater disappeared – double the capacity of India's largest surface water reservoir.

Typically there are groundwater shortages or the influx of salt water into coastal wells. Many farmers have been forced to abandon wells or keep drilling deeper. As remarked in Chapter 6: in parts of Gujarat in western India, the water tables have been dropping as much as 6 m during a year (Narayan Vyas, 2002). This is nothing else than hydrological suicide.

Subsidizing water and energy encourages waste.

The energy side: one reason that farmers in India, and throughout the world, have been heedlessly pumping water is that they have paid so little for it. In India the water itself is free, and the government heavily subsidizes the electric power for the pumps. Rather than pay for the used energy the farmers pay a low flat annual rate. It is estimated that the total energy subsidy to Indian farmers to pump up groundwater is about US$5 billion a year, more than 1% of the gross domestic product. Another consequence is that the power grid is regularly overloaded and too often electric power cannot be delivered.

7.3 SOME REGIONS HAVING TOO LITTLE OR TOO MUCH WATER

Too little water as well as too much water will create chaos and suffering. It is often misleading to describe water scarcity country by country. Problems tend to be more localized than that. One definition of water stress is that people use more than 40% of available renewable water. Just some obvious examples: the great lakes in North America are the world's largest freshwater basin. South western US is water stressed. Northern China is very dry compared to the South. Parts of India have hundreds of millions of people without enough water. Southern Spain is very dry compared to the North.

We will illustrate the water crisis by a short description of some areas that are getting hard hit by shrinking water resources. Some water scarcity regions are:

- The Gaza strip has the lowest per-capita availability of natural fresh water in the world. The area is already running out of drinkable water. There is an aquifer below the Gaza strip but as more and more water is pumped the porous rock is invaded by sewage from the towns and salty water from the sea.
- Southern Europe, in particular the countries around the Mediterranean sea, have got less precipitation, serious heat waves and many serious forest fires during the last decade.
- Water scarcity is not always where we expect it. England has less water available per head than Afghanistan and the southeast part of England has less water per capita than Ethiopia.
- Major world rivers are in a difficult state. The Yellow River in China (see Map 10.4) now barely trickles in its lower reaches. In recent years it has gone dry due largely to heavy irrigation upstream. It is not alone: the once mighty Nile (see Map 2.6), Ganges (India), and Colorado Rivers (see Map 10.5) barely reach the sea in dry seasons.

I saw Rio Grande, defining the border between Texas and Mexico, for the first time in 1975 (Map 7.1). Being interested in geography I had read about the fifth longest river in North America and had been looking forward very much to see the mighty river. What I saw was a shock to me: it was possible to walk across, and the water would not even reach the knees.

7.3.1 The Sahel region

Many regions in Africa have become drier. In particular, the Sahel region, south of Sahara, is one of the regions that seems to get not only temporary draughts but prolonged dry climate as a result of climate change (Zeng, 2003; Prospero-Lamb, 2003; Gianni *et al.* 2003). The crucial monsoons have more or less disappeared during the last four decades. Sahel has always been dry in the sense of low precipitation. Still farmers could survive in some areas while nomads moved their cattle where some feed was available for the animals. There is a common perception that the desertification is a result of overuse of the land; that people used too much wood for fuel and the animals destroyed the sensitive soil. Apparently this explanation is wrong.

Map 7.1 The Rio Grande river.

The Sahel drought depends primarily on global warming.

The reason for the Sahel disaster was published in 2003 by the US National Center for Atmospheric Research. The local population had only a minor influence on the precipitation in Sahel. Instead it was found that the loss of rain depended primarily on one variable, the temperature of the surface water of the Indian Ocean. This in turn was a result of the increasing GHG emissions. The Indian Ocean is heated up quicker than the other oceans and because of the rising temperature the conditions to build up monsoons will get weaker. This led to the permanent drought already in the 1960s. One of the hard hit regions is Darfur in Western Sudan (Map 2.6). Now there is a real danger that the dust blowing from the Sahel will have an influence on a global scale. Dust particles can scatter and absorb light which will result in decreasing temperature. The particles also contain nutrients that are spread from Sahel to the oceans and to other countries. For example, Florida receives a significant amount of dust from the Sahel region. So, the rich part of the world looks like the major cause of the problems in Sahel.

7.3.2 Australia

Australia that already has such a dry climate has been affected by an increasing lack of water. The precipitation has decreased around 15% since 1975, compared to the average for the previous more than 100 years. Climate models explains this by two factors. Half of the change is due to global warming, which has caused the temperate zone to move southwards. The other half of the model is believed to be caused by the destruction of the ozone layer. This has chilled the air above the Antarctica and moved the southern rainfall area further southwards.

The winter rains have decreased more than the 15% while the summer rains have become heavier. This has magnified the problems. The city of Perth in Western Australia (see Map 7.2) has been hard hit by the dryer weather. The city has applied advanced water savings programs and also installed desalination plants to manage the water supply for the city (see Chapter 20).

Map 7.2 The city of Perth, Australia.

7.3.3 The Pacific

A state of emergency was declared in the tiny Pacific nation of Tuvalu on 28 September, 2011 (Herald Sun, Melbourne). The nation of 10,000 had only five days of drinking water left. Tuvalu is located halfway between Australia and Hawaii and had not seen substantial rain since late 2010. The drought ended in April-May 2012. Tuvalu was in the grip of the La Niña weather pattern, which left it dry, but deluged Australia. A portable desalination unit from the New Zealand army was deployed on the main island, Funafuti. A Red Cross desalination unit has also been deployed on the island of Nukulaelae (Water 21 Global News Digest, 18 October, 2011). In response to the 2011 drought, Japan funded the purchase of desalination plants. Aid from EU and Australia provided water storage tanks to increase storage capacity and roof and gutter systems to capture more fresh water. In 2012 a UN Special Rapporteur called on the Tuvalu Government to develop a national water strategy to improve access to safe drinking water and sanitation.

7.3.4 US

Large parts of south-western US are hard hit by the lack of rain. There are obvious signs that the surface water temperature in the Pacific Ocean is coupled to the climate in western US. In the period 1998–2002 the water temperature in the eastern part of the Pacific was colder than normal, while the central parts of the western Pacific Ocean was around +30°C, much above the average. The GHG emissions were considered the cause of the temperature changes. As a result the jet stream was moved towards north, from about latitude 35° to 40°. This just shows that conditions in one part of the world will influence the weather and climate in other parts of the world.

Precipitation in Western US depends on the Pacific Ocean temperatures.

Some places are already pursuing water savings programs and clean energy policies. One example is the City of Albuquerque, New Mexico (USGS, 2014). Its water conservation program now saves around 70 million m^3 and 137,000 tons of carbon each year. Big investments are made in wind power that can replace hydropower. This saves around 6 million m^3 of water in the Colorado River (See Map 10.5). Water saved by transitioning to cleaner, less water-intensive energy sources can meet other future water needs and maintain higher stream flows.

7.3.5 China

In Northern China the water crisis is apparent. At the same time, large rain storms increase the risk of flooding during the rainy season. Still the dry season seems to be increasingly drier in many areas of southern Asia. For all of China the water availability is only 25% of the world average. Northern and Western China have only 1/10 of the world average. The water table under the North China Plain, which produces about half of China's wheat and corn, is steadily dropping. Perhaps 100 million Chinese eat food grown with groundwater that the rains are not replacing.

Serious pollution in the rivers exasperates the water resource problems. In 2008 two thirds of the nation's total water consumption came from aquifers, and the water tables keep falling.

Water is scarce around Beijing, where groundwater is overexploited. The water availability in Beijing per capita is only 15% of the national average. In 1950 the groundwater level in Beijing was 5 m below ground. In 1994 it was 50 m below. According to the Chinese authorities the level has gone down half a meter per year.

The construction of a major canal from South to North, from the Yangtze River to the Yellow River (see Map 10.4) and Beijing, is envisaged to alleviate water scarcity in the North. Seasonal variations of water availability, causing floods and droughts, are a major problem. Industrial pollution affects numerous rivers.

According to China's State Environmental Protection Agency (SEPA) in 2006 60% of the country's rivers suffer from pollution to such an extent that they cannot be used as drinking water sources. The Yellow River is one of the most serious examples of the serious water conditions in China. During the record breaking 1997 there were 227 days with no water towards the outlet (see further Section 10.3).

In 2002 there was a new water law in China. The goals are: integrated systems for river management, local engagement in water usage, polluter pays principle, and an adequate water pricing. (Hanson-Martin, 2006; Varis-Vakkilainen, 2001; Naughton, 2007, page 500).

7.3.6 Water flooding

A great fear of climate change is the extremes, either water scarcity or flooding. During 2010 and 2011 some very serious floodings have devastated Pakistan and Thailand. Also in other places there have been extreme rainfalls for example in Italy in the fall of 2011. Queensland had been hit by a long drought, and when the drought was at its worst, many feared that the rain that sustains the population was gone forever. But the rains returned in early 2011 and Queensland got more than enough. The dams were filling and it is possible that water from the new desalination plant will not be required for many years.

7.4 WATER SECURITY AND WATER SCARCITY

The global consumption of water has increased quite remarkably during the last 50 years, as illustrated in Figure 7.2. Part of this consumption is the increased evaporation from all the water storages that have been constructed in the period. Many reservoirs are multi-purpose, serving both hydropower, water storage and flood control. However, the increased evaporation demonstrates that the water storage and dam building comes with a price that is often very high (see further the discussion on evaporation in Chapter 10).

The Asian Development Bank states in its report (ADB, 2013b) that water scarcity will increase dramatically in many parts of the world. This will have significant social and economic repercussions. Global grain harvests will be threatened, more countries will rely on food imports, and the livelihoods of many people will be threatened. This is on top of the billion or so people who do not have access to improved water supply today.

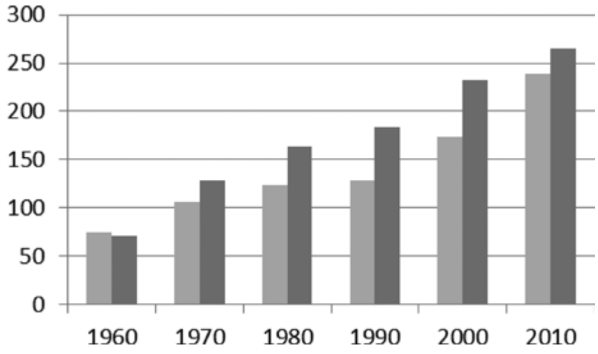


Figure 7.2 The development from 1960 to 2010 of global consumption of water (measured in km^3). The left bars indicate the industrial and domestic consumption and the right bars show the evaporation from reservoirs in km^3. (*Source*: UNEP, www.unep.org/dewa/vitalwater (15 Jan. 2015).)

Global demand for food, especially meat, will rise sharply, placing more pressure on water for agriculture. Unless we change how we manage agricultural water, we will not be able to provide the food for tomorrow's consumer demands. Compounding the problem, fast-growing economies, especially in the Middle East and Asia, will likely allocate less water to agriculture over the next two decades and more to the growing demands of their urban, energy, and industrial sectors.

The over-extraction of freshwater is compromising the environment severely in many parts of the world. Climate change adds to the urgency; its impact is demonstrated most prominently in water resources.

Improving water infrastructure for cities, energy, and industry will become urgent across all economies. Poor quality and inefficient water supply services will be seen as a brake on economic growth.

Many international actors, like ADB and World Economic Forum, agree that management of future water needs stands out as an urgent, tangible, and fully resolvable issue, which can only be improved by a multi-stakeholder effort led by government. Governments can bring business and civil society together to help address a commonly (and often locally) felt challenge. While some trade-offs will be inevitable, all can benefit from improvements in how water is managed.

Energy policy decisions have strong connections to water, climate, and food security policy, which can spin negatively or positively. Energy policy must take into account these interlinkages. Domestic energy security should be seen as a decision to switch from relying on foreign oil to relying on renewables and on domestic water.

The global water forecast for the next two decades, if no reform actions are taken, is chilling; water scarcity will have a profound effect on global and regional systems, whether from an economic growth, human security, environmental, or geopolitical stability perspective.

7.5 A SYSTEMS APPROACH

We emphasized in Chapter 3 that the complex web of issues involved in providing a growing population, increasing food and energy need and the apparent increase in water demand requires an integrated systems approach. Various scientific models are getting developed to deal with these global complex problems in order to identify effective policy options. International organizations like IIASA, FAO of the UN, the UN Environment Program, and the World Meteorological Organization are involved in these efforts.

Systems are needed to provide appropriate, timely and readily applicable mitigation, warning, management, and adaptation methods in case of extreme events. These need to provide advice at appropriate spatial and temporal scales, from minute for emergency services, to decades for effective adaptation to climate change. Floods and droughts can be worsened by poor land management and the effects of climate change, and need to be tackled in an integrated way.

An integrated thinking requires that we understand how water, energy, food and land use are interconnected. Figure 7.3 illustrates the global driving forces in terms of population growth, climate change and an increasing urbanization and that the impact is noted in energy, water, food and land use. In city planning, infrastructure planning, energy production planning or food production strategies we all the time have to consider that all these systems are interrelated. This puts a lot of pressure not only on governments, decision makers and policy planners. It has to have a profound impact on the way we educate our engineers, social scientists, architects or city planners.

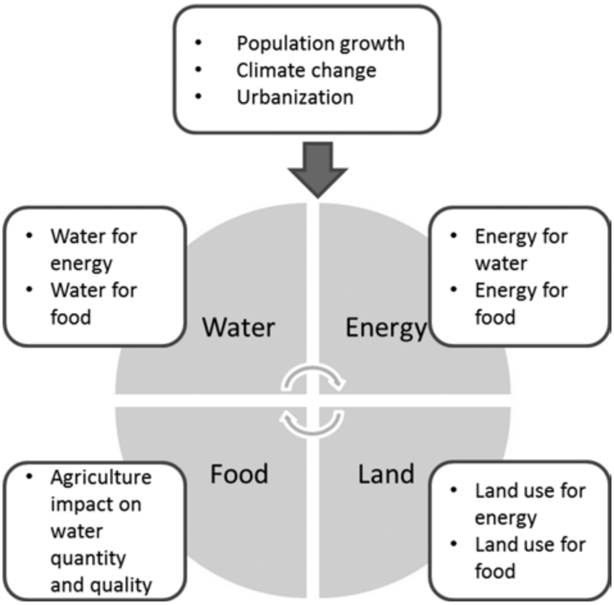
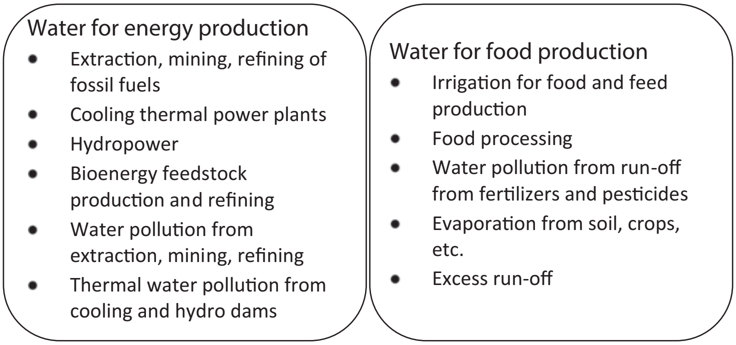


Figure 7.3 Water, energy, food and land use are closely coupled to each other.

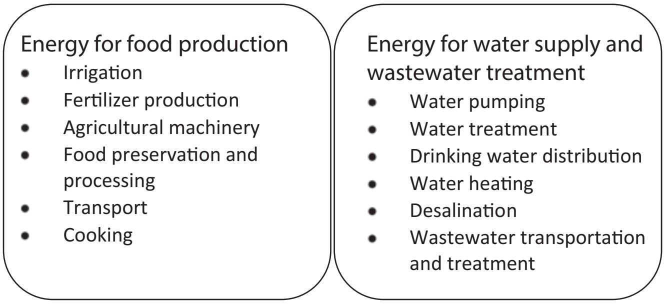
In Figures 7.4 and 7.5 we illustrate more details of the couplings. Water for energy production is the topic of part III of the book while water for food production was discussed in Chapter 6. Food production also depends on energy, Figure 7.5, while energy for water supply and wastewater treatment is the topic for Part IV of the book.



Water for energy production
- Extraction, mining, refining of fossil fuels
- Cooling thermal power plants
- Hydropower
- Bioenergy feedstock production and refining
- Water pollution from extraction, mining, refining
- Thermal water pollution from cooling and hydro dams

Water for food production
- Irrigation for food and feed production
- Food processing
- Water pollution from run-off from fertilizers and pesticides
- Evaporation from soil, crops, etc.
- Excess run-off

Figure 7.4 Water uses for energy and food production.



Energy for food production
- Irrigation
- Fertilizer production
- Agricultural machinery
- Food preservation and processing
- Transport
- Cooking

Energy for water supply and wastewater treatment
- Water pumping
- Water treatment
- Drinking water distribution
- Water heating
- Desalination
- Wastewater transportation and treatment

Figure 7.5 Energy uses for food production and water operations.

Land use is becoming increasingly urgent to handle, which has been discussed in Chapter 6. Land use for energy production is related not only to biofuel (Chapter 12) but also to the land use of other energy sources. The land use for oil, gas and coal is sometimes very difficult to define and depends how the extraction processes are described (Chapter 11). For hydropower there is a discussion in Chapter 10. Various renewable energy sources and their land use are considered in Chapter 22.

It is obvious that a new thinking has to guide the future water systems design and operation. The traditional solutions to water scarcity have been to supply water from ever increasingly distant sources – the civil engineering solution. In many places this type of solution is no longer economically or politically acceptable. The alternate solution to water stress has been to treat and use the locally available water resource – the chemical engineering solution. While incremental improvements continue to be made in treatment technologies these systems have reached the limits of their technological and economic effectiveness. This is also due to the increased number, complexity and variety of pollutants and the public's environmental expectations.

Flexible and adaptable solutions to cope with water stress are needed to reduce vulnerability and ensure that the available water is used in the most efficient way. In the last twenty years there has been an increasing emphasis on demand management (Chapter 8), and particularly in educational programmes to encourage public and private user communities to conserve water and to improve the efficiency of water use.

7.6 CHAPTER SUMMARY

Climate change, population growth and our changing life styles have a profound influence on water resources.

- The consequences of climate change seem to go both ways, either towards drier climate or towards more flooding and heavy rains.
- Other serious influences of climate change is melting glaciers, salinization of water supplies, increased frequency of extreme weather patterns, both floods and droughts.
- Examples of regions are given, where the water issue is becoming a serious problem, either too dry or too wet.
- Groundwater resources are threatened in many places, both due to too much extraction and due to serious pollution. Shallow wells obtain their water from groundwater that recently was surface water and therefore subject to greater contamination.
- Most but not all bacterial contamination of water supplies stems from the use of surface water; rivers, lakes and reservoirs.
- Many of the described problems cannot be solved in isolation. They have to be treated in an integrated way, where both supply and demand are taken into consideration.
- An integrated thinking systems approach requires that we understand how water, energy, food and land use have causal links.

7.7 MORE TO READ

De Villiers (2001), Pearce (2006), Solomon (2010), Fishman (2011) and Maxwell-Yates (2011) give a broad picture of the overwhelming problems of global water resources and present challenges for both decision makers and customers. Climate change influence on water resources is very well described by Flannery (2005), including the challenges of the Sahel region and the El Niño – La Niña cycle. Ljunggren (2008, Chapter 5) gives an excellent overview of China's environmental problems. Unfortunately the book is published in Swedish only.

8 Opportunities – the water demand side

> *The difference between what we do and what we are capable of doing would suffice to solve most of the world's problem.*
>
> Mohandas Gandhi

> *Water, taken in moderation, cannot hurt anybody.*
>
> Mark Twain

It is getting increasingly clear that humanity can survive only by living within the limits of physically and economically available resources. In this context, fossil fuels appear analogous to winning a lottery ticket, or inheriting a fortune, which indeed is exactly what it is. Our water and energy systems have mostly been designed from a supply oriented philosophy. We probably have to revert this to a demand side management strategy. This naturally requires a different way of handling the systems. First of all it is crucial to create adequate driving forces that would encourage efficiency and at the same time be affordable for the poor.

8.1 CONSUMER ATTITUDES AND LIFESTYLES

So far demand is treated as a given; it is rarely managed or controlled, and it drives supply in the developed world. The per capita average water use in some countries is displayed in Figure 8.1.

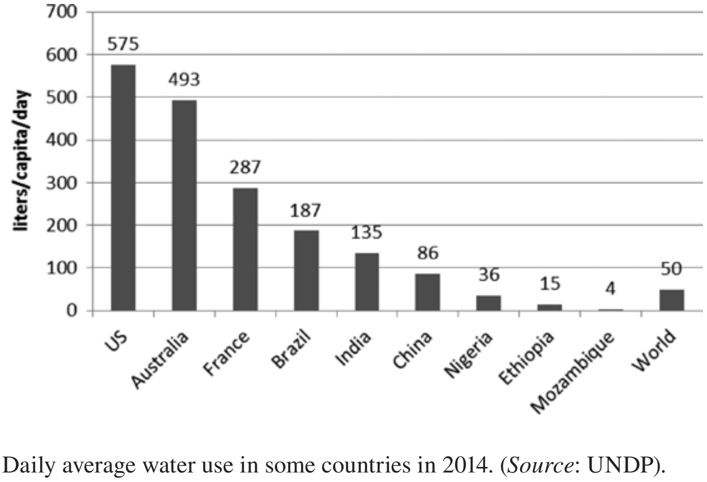


Figure 8.1 Daily average water use in some countries in 2014. (*Source*: UNDP).

It is apparent that the water consumption does not correlate with economic development. In highly developed European countries like Germany or the Netherlands the domestic water consumption is quite low compared to North America. These figures are hard to compare directly, since they may not account for climatic conditions or what the actual uses are (e.g. there is little lawn irrigation needed in the Netherlands). However, they certainly reflect some of the patterns in consumption, driven by relatively high water prices and the culture of low domestic use that is dominant in most European countries but still quite foreign in the US. The agricultural water consumption in the US is also increased by the high protein meat diets that is typical for the life style.

Not all the answers to climate change or the water shortage challenges are technological – maybe not even most of them. Many of the paths to stabilization run straight through our daily lives. In some cases they are changes of attitudes, in other cases they involve difficult adjustments. This includes how we use hot and cold water for showers, dishwashers and washing machines. What kind of machinery is used? How do we consume water for gardening and so on? As an example, the long drought in Queensland, Australia forced the authorities in Brisbane to enforce a decreasing consumption. In 2005 the consumption was 300 liters/cap/day and in 2007 it had decreased to 130 (Keller, 2008). This included restrictions for external water use and recommendations for internal water consumption.

As the world population grows the demands for both water and energy increases faster than ever. It looks as if the world has become aware of the era of peak oil, seeing the fluctuations of the oil price. It seems that we are approaching an era of peak water – there will be lack of cheap water.

> The situation should already be considered a crisis, but the public in many developed countries has not grasped the urgency. Water is ultimately more important than oil, because it is more immediately crucial for life.

Our mobility in the developed countries has a high environmental price. Air travel is one of the fastest growing sources of carbon emissions around the world. We may be happy to change light bulbs and to drive hybrid cars, but the thought of decreasing the travel will involve some sacrifice. Driving alone in cars in too common in western countries. This is considered more convenient than to adjust to the schedules of public transport.

Our diet has a lot of carbon and water footprint, as discussed in Chapter 6. Some recent study in the US has shown that the average bite of food has travelled nearly 2400 km before it reaches the mouth.

Our homes are bigger in the West while the family size shrinks.

8.2 WATER PRICING

> *Nowadays people know the price of everything and the value of nothing.*
> Oscar Wilde

Most of us have only a vague idea what we pay for water and a majority of consumers do not have any water metering for the apartment or the family. At a public presentation on water and energy I asked the audience: ‘how many of you have at least a rough idea how much you pay for the electrical power, per kWh?' Most of the listeners had a feeling for the price. Then: 'how many of you know how much you pay for the water?' One (!) out of about 200 people had a feeling for the numbers – and he was employed by the local water company. This seems to be quite indicative. Water is considered so cheap, so why care about it.

Let us look at the water tariffs. Figure 8.2 shows the water consumption in 104 cities all over the world as a function of the water tariff.

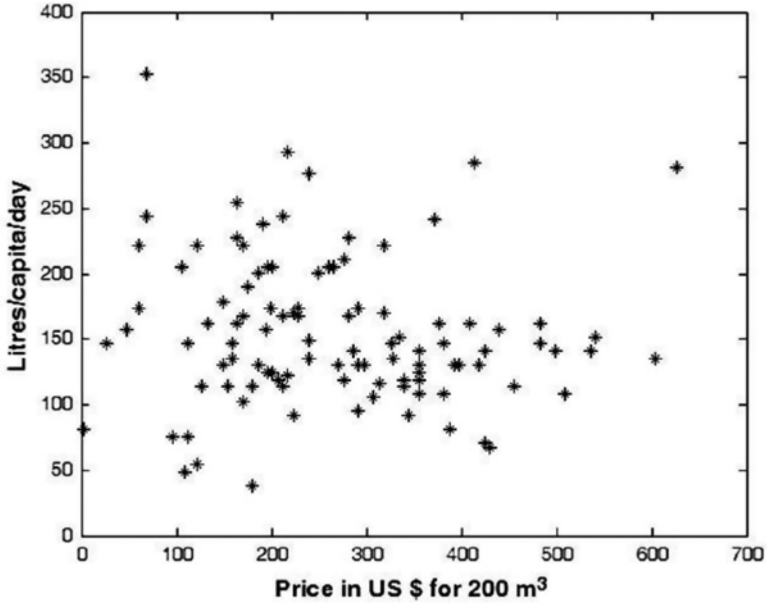


Figure 8.2 The consumption of drinking water as function of the total charge for 200 m^3 in 104 cities around the world. The charge for 200 m^3 is from 3 to 626 US$ and the consumption from 0.34 to 650 liters/capita/day. (*Source:* IWA International Statistics for Water Services. IWA Specialist Group Statistics and Economics, Vienna 2008).

It is quite obvious that there is no correlation between the water pricing and the consumption. We would have expected a smaller consumption for a higher tariff. Then we may object that the consumption is related to the prosperity, so let us calculate the consumption as a function of the GNP, Figure 8.3.

Again, it is obvious that there is hardly any correlation, so in some way the water tariff does not provide any driving force to make the consumption efficient.

Typically the total water price is divided into two parts, one fixed annual (or monthly) cost and one proportional to the consumption. The relationship between the fixed cost and the total cost may be quite different, even in the same region within a nation. Figure 8.4 compares the annual cost for 150 m^3 of water in some communities within a county in Western Sweden. There is a factor of three between the lowest and the highest fixed costs and also around a factor of three ratio between the lowest and highest operating costs. Obviously the customer with the high fixed cost has got less incentive to reduce the consumption. In Sweden the average operating tariff in 2005 was 14.95 SEK (around €1.6) per m^3 and the fixed annual cost 11.96 SEK (around € 1.25), calculated for a family using 150 m^3 per year.

This means an average tariff of 26.91 SEK (around €3) per m³. There is a wide difference in tariffs within Sweden. In the most expensive municipality the price is almost four times the price in the lowest cost municipality (STEM, 2012).

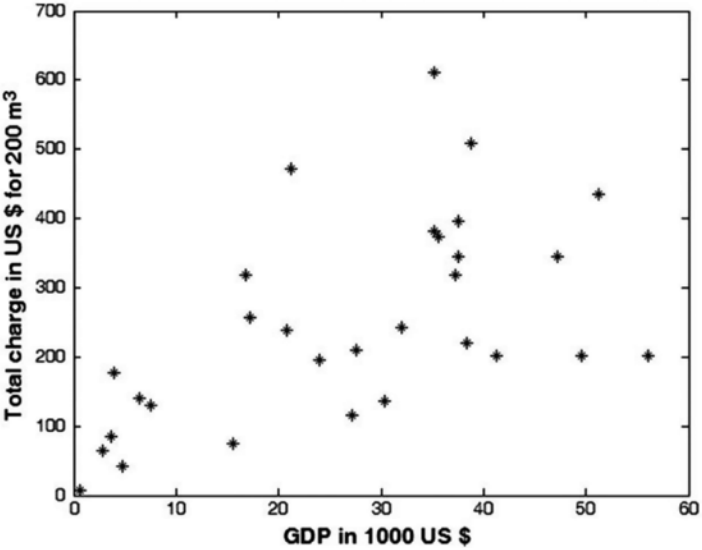


Figure 8.3 The total charge for 200 m³ of drinking water compared to the GDP in 30 countries from Europe, Africa, Asia and Australia. US and Canada and South America are not included. (*Source:* IWA International Statistics for Water Services. IWA Specialist Group Statistics and Economics, Vienna 2008).

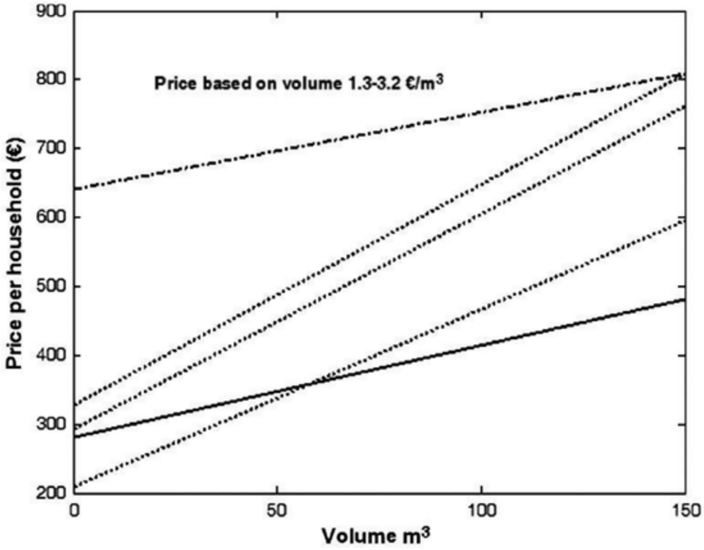


Figure 8.4 The cost for water (in Euros) for households in five municipalities in western Sweden. The volume of 150 m³ is the expected yearly consumption of a family.

Comparing the fixed and operating costs in the 104 international cities shows similar differences. Figure 8.5 reveals that the fixed part of the total price for 200 m^3 is significantly different between the cities.

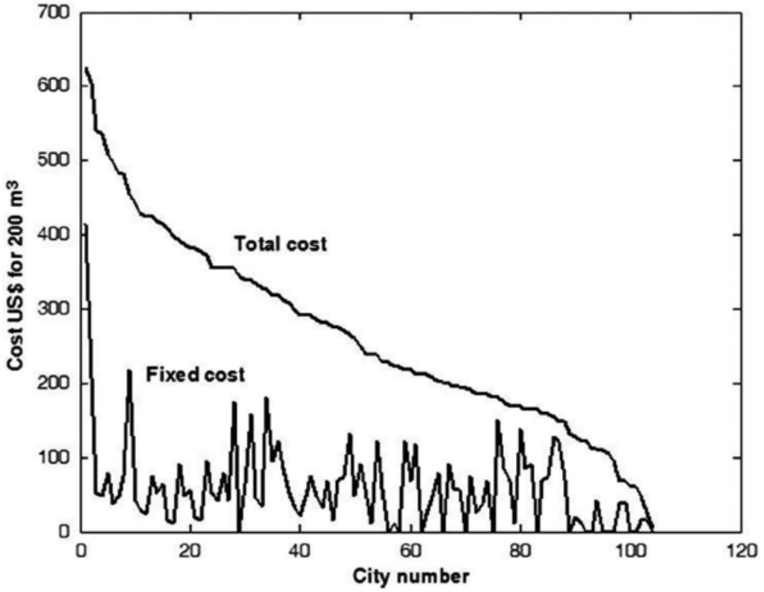


Figure 8.5 Comparison of the fixed (lower curve), floating cost (for 200 m^3) and the total charge for 200 m^3 in 104 cities around the world.

Some countries have recognized that the tariff should encourage efficient use of the water. One example from Greece is shown in Figure 8.6. The first 100 m^3 have a fixed price and no operating cost. More consumption will cost more per m^3. Many cities in China have the same kind of progressive pricing that will encourage reduction in the water use. It is obvious that the revenues have to be sufficient to operate the utility efficiently and to extend the service to potential new users. Figure 8.7 shows progressive tariffs in some Asian and African cities. The exact tariffs are continuously updated, but the principle remains.

Naturally the low or zero tariff applied to the first liters consumed can enhance affordability. For example, Durban, South Africa, provides the first liters of water a day free of charge – a lifeline to many – with a steep increase above this level. Higher tiers aim at enabling utilities to increase efficiency by creating disincentives for overuse. At the same time they have to collect revenues to cover costs. Many countries apply a low tariff for an initial volume of water, though few countries follow South Africa's policy of free water. The size of the baseline tariff and of the increments between blocks varies across countries.

Under the right conditions rising block tariffs can enhance water access and equity. But outcomes depend on a range of factors. In many utilities tariffs are set far below the levels needed to meet the overall costs of operation and maintenance. Subsidizing water strategies depends a lot of the relation between connected low-income and high-income households. Cross-subsidies from high-consumption (high-income) to low-consumption (low-income) households are effective only if a sufficient number of customers use the higher blocks. An obvious danger is that excessively high prices will drive users to alternate sources of provision.

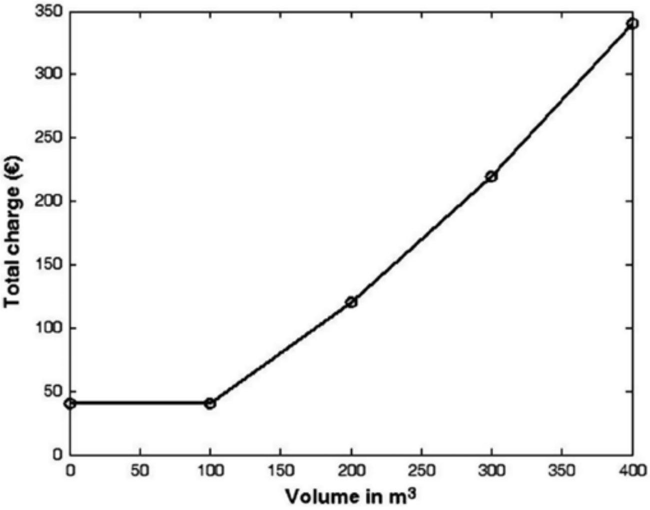


Figure 8.6 Example of progressive pricing (from Skiathos, Greece). For the first 100 m³ per year only a fixed base tariff is paid. Then the tariff is 0.8, 1.0 and 1.2 €/m³ for every additional 100 m³ respectively. (*Source:* Personal interviews.)

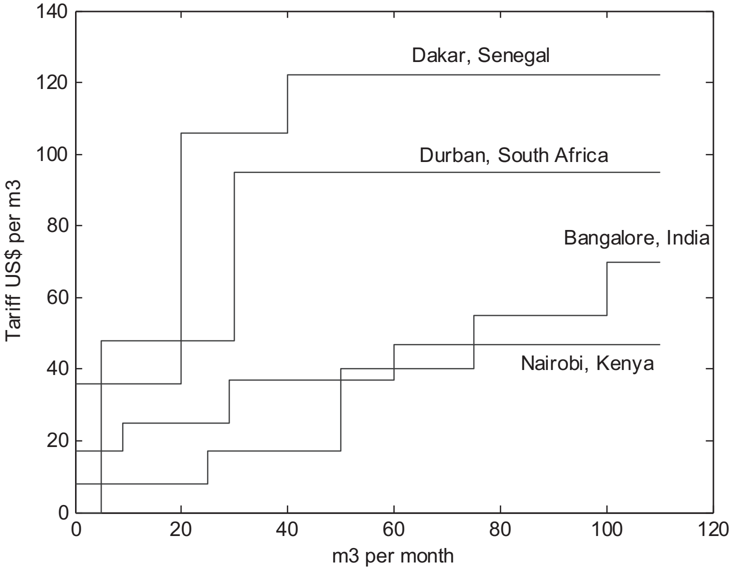


Figure 8.7 Progressive prices in some cities in Africa and Asia. (*Source:* UNEP (2008).)

Block tariffs can also create structural disadvantages for the poor, as described by UNDP. Many private operators supplying households without private connections often purchase water in bulk at the top price. Thus, water vendors and truckers are reselling the highest cost water sold by utilities. Similarly, when poor households group together to share a metered connection (a common arrangement in many countries), their aggregate consumption level pushes them into the higher price tiers.

Still another problem has appeared when water savings programs were too successful: the water pipes were simply too wide and the resulting water age increased, so that the water quality suffered. This just illustrates another aspect of this complex issue.

8.2.1 Water pricing for irrigation

The irrigation of water in the Central Valley of California has been remarkably cheap, far below the cost of collecting and transporting the water. This makes it affordable not only to irrigate the farmlands but also to keep the fairways and greens of the golf courses.

For the farmers the price should be set at a level that would encourage sustainable practices. If the governments stopped subsidizing water to plants and water-thirsty crops alien to deserts or to irrigate pasture to raise cattle for beef (at a ratio of 15,000 kilos of water for 1 kilo of beef) and if we stopped to do the wasteful things we would have water to spare.

8.2.2 Leakage – a cost in both water and energy

One of the reasons for high leakage in many urban areas, particularly in the developing world, is that people are paying too little for the water. If a shower or a toilet is broken the water just will run.

Efficiency is primarily obtained by systematic and simple maintenance, repair and operation. Durban, South Africa, can be used as a role model for water operations. In 1992 Durban had one million people living in the city proper and another 1.5 million people, almost all black, who had moved into shantytowns or were living in housing projects just outside the city. It was estimated that 42% of the region's water was wasted because of broken water pipes and mains, leaky toilets and faulty plumbing. In two districts with a combined population of half a million 87% of the water was being lost due to leaks and other wastage. Since people were not paying for water, they just let it run in a leaking toilet. A crash program was initiated. Mains were repaired and replaced. Water meters were installed. Toilets were replaced to low flush toilets. Showerheads and taps were retrofitted. For the poor were installed tanks in homes and apartments to provide 200 liters of water a day for free. As a result, six years later the water consumption was less, even as another 800,000 people had received service. The conservation measures paid for themselves within a year.

Leakages will be more discussed in Chapter 16.

8.2.3 Reflections on pricing

Providing water as a service available on demand, piped to every home and industry in the land, is a mark of development and modernity. But that does not mean it should be supplied for free. Clean water requires treatment and a vast infrastructure and distribution do not come cheap. The water industry benefits from being run on a profit-and-loss basis, reflecting the true price of the precious resource. In many countries it is undertaken as a public utility fully paid for by the taxpayer. However, the cost of accommodating growing demand is too high for the public purse.

Access to clean water, however, is also a human right, hence the conundrum: is the economic cost of treated water within the means of every consumer? The answer is probably no in most developing countries. If priced correctly according to market evaluations, there will be some who will have to use water so frugally it could pose a danger to personal and public health. In poor countries, even in the middle of cities, people are resorting to untreated groundwater for the daily needs. In these circumstances, outbreaks of cholera and other water-borne diseases are a regular occurrence, especially where a proper sewerage system is lacking. For public health and other reasons, every household should have access to treated, piped water – but at a price structure that incentivises conservation.

> Subsidies should only go to the truly deserving.

Water delivery is too expensive to be paid only by tax money. Yet, there is a need to ensure that every human will have the right to clean water. At the same time, expecting consumers to pay entails a binding contractual agreement that they get what they pay for, water that is drinkable from the tap and clear of all known health hazards. Water should no longer be considered as falling from the sky. It is in fact an increasingly scarce commodity whose purveyance must comply with rules, regulations and the principle of fair trade.

Water pricing needs to be revised in many places and countries. The closer the price of water approaches full cost; the better water could be valued.

> In many countries, both developing countries and industrial countries, water is massively subsidised, subjecting it to serious under-valuing and serious misuse by individuals and industry.

8.3 THE VALUE OF WATER

In Chapter 1.3 we discussed the diamond-water paradox. The value of water is related to its marginal value. It also means that everybody should be able to pay for the water that is needed for supporting the life and for cooking and basic hygiene. In other words, do not charge what people can pay but according to what the water is worth, taking into full account the development costs of delivery systems, including wastewater treatment.

8.3.1 Water pricing

We have seen that many places charge the water so that even the poorest people can afford a minimum amount of water use.

> A fair pricing would be to allow minimum water consumption – the lifesaving water – at an affordable rate.

It has been suggested that this number could be 50 liters per person per day: 5 liters of drinking water, 20 liters of sanitation water, 15 liters of bathing water, 10 liters of food preparation water. Anything above this level should be priced according to the real costs to make the water drinkable. To water a lawn in a water scarce area is not a human right and should be charged accordingly. This is qualitatively illustrated in Figure 8.8. It is crucial to find some technique to determine the economic value of water services. This is of course related to the willingness to pay. It looks as if too many countries and governments consider water as a limitless natural resource that can be freely exploited and used by any authority or by the land owner. Opposite to any other commodity – such as oil – there is hardly any market defined for water. Only the cost of pumping and distributing the water is commonly charged.

> There is mostly no cost given for the degradation of the water ecosystem.

To pump the water from a river or other surface water makes no difference than pumping the water from an aquifer. The water seems to belong to everyone and nobody has the responsibility.

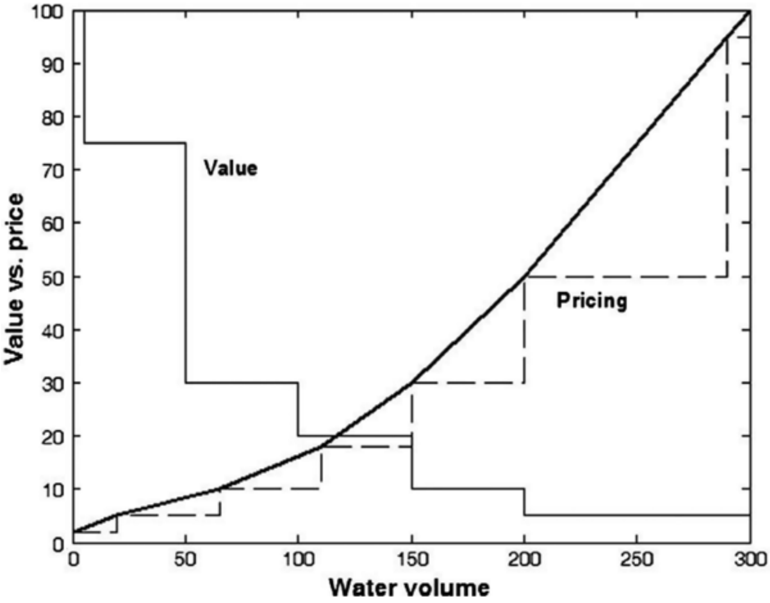


Figure 8.8 The perceived value of water compared to a structure of the tariff.

> There is often a huge under-pricing of water. It sends a signal that the water supply is unlimited.

The environmental catastrophe in the former Soviet Union of the disappearing Aral Sea (see Map 2.2) may be the most frightening example of devastating misuse of water during the last century.

We have to inform the public more about the value of water, not only the cost of water. The water value has to be protected, not the water cost. Water is really the oil of the 21st century.

8.3.2 Water footprint

We have to connect water usage to the water footprint. If the water is pumped from surface water that is replaced, then the water footprint would be small. In that sense this water supply is sustainable. On the other hand if too many users would extract water from the same well, river or reservoir, then of course we have a water footprint that is not acceptable. The same would be true if we consider virtual water, the water that is connected to food. It is well-known that the production of 1 kg of beef requires a colossal amount of water. However, if this water is replaced by rainwater, then the water footprint in the sense defined above would be small. The problem is that too much beef today is produced where the water is not replaced.

In rich countries we may consider moving the water from a water rich area to a water scarce area. In principle this is possible but the energy cost is mostly prohibitive.

> Water is heavy and cheap. Therefore it is not profitable to transport the water long distances.

We find obvious exceptions. The water supply to Southern California is one of the most advanced systems, and water is pumped from both Northern California and from the Colorado River (see Map 10.5). Naturally the energy cost for water supply is remarkably high (see further Section 15.3).

8.3.3 Cost of water scarcity

The price for water availability can be defined in many different ways. Considering the fact that about one billion people lack readily available clean water we may look how the basic needs can be provided. Accordingly we may consider the cost of not providing the basic water for drinking and sanitation. These costs are phenomenal but seldom displayed clearly. According to the UN Secretary General there is probably a payback of $7 per $1 invested to get clean available water. Instead of treating all the illnesses caused by unclean water we can avoid many of them. School-children will be able to go to school instead of taking care of sick brothers and sisters at home. And then: all the children dying from contaminated water, 1.8 million every year (Section 1.2).

The time being spent (mostly by women and girls) to fetch water, most often of a very unsatisfactory quality, is phenomenal. It is calculated that only in Africa some 25 million man-years (women-years!) are spent to fetch water. Naturally this human resource could be used in a better way to improve the quality of life for so many people on the continent. What kind of alternative income could have been gained by these 25 million man/women-years?

The value of water for the rural family in a water scarce area in Africa is high. If you have to spend three hours to carry home the 20 liters of water, then the value is different than if the water is provided via the tap in the kitchen.

8.3.4 Water economy

We can conclude that water pricing should reflect not only production costs but also water availability and energy availability. Conventional economy does not calculate the cost for water degradation. To pump water from a lake is not considered different than to pump fossil water from an aquifer.

The economy of water sometimes resembles the economy of ecology. Biodiversity brings stability to ecosystems, which provide a wide range of 'services' that businesses rely on, yet received free of charge. Because there is no financial cost for these services, they have been treated as being without value. This has resulted in corporate decisions that damage the ecosystem, reduce biodiversity and leaves fewer degrees of freedom for future action. They also put the resources the business relies on at risk.

The solution is to value these ecosystem services so that they can become part of planning and decision making. This has nothing to do with corporate social responsibility and the green agenda, it is hard-nosed economics. If the economic values of those services are taken into account, decisions automatically promote sustainability. For instance

> the cost of water is not just the cost of operation but the value for future generation, for recreation, tourism and so on.

8.4 THE CONSUMER – RAISING THE AWARENESS

It should be emphasized that more than 90% of the water related energy use is spent in the home. This is true for many industrialized countries. This aspect is further elaborated in Chapter 21.2–21.3.

The fact that the water companies usually consume only some 10% of the energy in the water cycle makes it crucial to carefully consider the consumer side. Many water companies do not wish to take the responsibility for the domestic use of the water. Still, they usually have a good contact with the customers and should be able to easily influence the greenhouse gas emissions. The lesson is quite simple: reduce the warm water consumption. The consumption of warm water is not only a local issue. Even if there is plenty of water available the energy needed to heat it generates a carbon footprint, and this has a global impact.

8.4.1 Importance of metering

We all need feedback. To measure is to know. In most multi-apartment buildings there is only one water meter for the whole building. So, the customers do not know their individual consumption. This invites to a lot of waste, both of cold and of warm water.

It is cheaper to measure electrical energy consumption than to measure water consumption. Consequently we usually have individual energy meters and become aware of the electrical energy consumption.

If we have no measure of our consumption we are not aware of our footprint. This is simple psychology. The introduction of individual water meters makes the users aware of the consumption. An interesting experience comes from Seattle, US. In one pilot project individual water meters were installed. Even before the meters got installed the water consumption decreased some 25–30%. Awareness had been created (Reiter, 2012).

In Sweden it is found that the total water consumption decreases by 20% if there are individual water meters. The warm water consumptions vary a lot. For apartment buildings in Sweden (with only one water meter) the warm water consumption is 30 ± 15 m^3/capita/year or 80 ± 40 liters/capita/day. For one family homes with individual metering the corresponding warm water consumption is found to be 14 m^3/capita/year. In other words, warm water consumption in apartment buildings without individual measurements is about twice as high as for one family houses (STEM, 2012).

8.4.2 Finding incentives

There are serious weaknesses in the pricing of both electricity and water in many parts of the world, which send the wrong signals to consumers about the need for conservation of both of these resources. Utilities or governments are frequently not sufficiently focused on the need for efficiency of use and conservation. The cultures within the water and electric power sectors are often quite different and there is too seldom sufficient communication between them to exploit the potential synergies of the two sectors.

Availability of both energy and water is essential for human survival and national prosperity. In a lot of regions a strong case can be made for policies and regulations that address water and energy simultaneously. This is not a technological challenge. The technology is there, but it is a political and organizational issue, for example:

- TV – Media – water operators: increase people's awareness and appreciation for water and energy conservation;
- More training, communication and knowledge dissemination;
- Better understanding of public perception;
- Innovative policy and legislation;
- Understand consumer expectations and perception around water issues as well as the way system solutions are accepted within communities.

Information and monitoring is one important issue. Concerning the water pricing and tariffs we have to find creative financing:

> It has to be full cost recovery for those who can pay; but: Affordable for all.

Again, information can influence people's willingness to pay. Key performance indicators should be published, including operation performance, leakages and technology progress. The customers should be aware of the true costs for operation and keeping the infrastructure – in a simple and understandable way. We will focus more on the demand side in Chapter 22.

8.5 GOVERNING WATER AND ENERGY

Usually our countries have government ministries of energy. Considering the importance of water we should have a Ministry of Water that would ensure the effective use of water, or better: one Ministry of Energy, Water and Environment. Water is certainly a human right, but it should not be free or cheap. If we think that water is important, we should put a realistic price on it. The attitude towards water consumption may be the crucial ingredient. New approaches to financing, managing and maintaining systems must be developed, as well as approaches to involve local communities.

As often in connection with water operations, Singapore can be a role model. With few natural aquifers and groundwater, Singapore has to rely on a diversified water supply referred to as the 'Four national Taps': imported water from Malaysia, local catchment water, NEWater (high-quality reclaimed water) and desalinated water. Water pricing is a key to managing water demand as explained by Prime Minister Lee Hsien Loong at the Singapore International Water Week in 2011: '… if you get the water for free, nobody will bother to turn off the tap. We have … moved our water rates to approximate the true economic value of the resource. We have the conservation tax so that we encourage people to conserve water … we also have schemes to help low-income households directly, so that nobody will feel that they cannot afford water to drink.'

The water and energy nexus has to be recognized by decision makers, researchers and engineers as a vital one. It will not only determine the way to extract, treat and distribute water and collect and treat wastewater. The role of water has to be fully recognized in the production and generation of energy, both for electricity and for transportation. Creating the right pricing, policy and regulatory environment is critical to encouraging behavioral changes, and ensuring a sustainable use of water and energy.

Water is energy and energy is water. That is why conservation of energy as well as an optimal use of water saves both water and energy.

As noted by Water Aid it is essential, especially in the developing world that a community understands that it is necessary to make some payment for the water that is used. The method of payment will vary according to the type of system and the nature of the users. It may be payment to a caretaker for each jerrycan collected, probably the most equitable way. However, this requires honesty and integrity from both the caretaker in handling cash and the user in offering payment. A monthly charge per household is easier to collect, but visitors, nomads or travellers will not contribute. Also, excess water used for irrigation or cattle watering is not covered by this method of charging, and there is no incentive to prevent wastage. All accounts should be managed by some person who is respected within the community and should regularly be made available for public scrutiny. The community must decide what method, or combination of methods, it will use to build up funds for future maintenance.

8.6 CHAPTER SUMMARY

- Our water and energy systems have mostly been designed from a supply oriented philosophy.
- We have to revert this to a demand side management strategy.
- Our life style has a major impact on both energy and water.
- Water tariffs are mostly not related to the value of the water.
- Current subsidies too often lead to misuse of both water and of energy.
- Feedback is crucial: it is provided both via metering and via easily understandable key performing indicators to the customer.
- We have to find incentives for a wise use of water and energy.

8.7 MORE TO READ

The UN report WWAP (2011) on World Water gives a wealth of information. Chapter 12 in the report discusses valuing water. De Villiers (2001) and Solomon (2010) discuss extensively about the value of water.

PART III

Water for energy

Water is absolutely essential to produce, distribute and generate energy. Whether that water will be available for energy systems, or whether competing uses such as agriculture and food production will produce scarcities, and where those problems are most acute, is the subject of this book. Water will almost certainly be more costly and valuable every year, as value added processes in energy and industries require increasing amounts of water.

Paradoxically, water is generally less expensive on a per unit basis in developed societies. Poorer regions pay most for their drinking water. At the same time, high income nations face the need to reduce their carbon footprint and to develop a new high-quality standard that is more sustainable. Such a development should inspire and encourage developing regions.

Since the first edition of this book in 2012 the attention to water for energy has increased remarkably. UN released its report on Water and Energy (UN WWDR, 2014), BP supported the publication of Williams-Simmons (2013), the World Bank published its report on Thirsty Energy (World Bank, 2013), a lot of new evidence on the influence of fracking on water quantity and quality has appeared and new evidence of long term consequences of serious oil spills have been found. Also, the Stockholm World Water Week in 2014 was devoted completely to the theme 'water and energy'. The author has also been involved in several new research projects on water and energy in various countries around the world.

The '**water footprint**' (the amount of water consumed to produce a unit of energy) of different methods of fuel production shows how water consumption for operations making primary energy carriers available vary from fuel to fuel. Analyses explore the water needs of a range of energy sources, including crude oil, natural gas, coal, uranium, and biomass.

The carbon footprint policies, adopted by many countries, look for replacements of fossil fuels. The increasing use of biofuels and the application of carbon capture storage (CCS), however, will have large implications on water. Some solutions look more attractive from a water perspective: wind and solar PV as well as natural gas combined cycle to displace coal and natural gas fuels to replace petroleum. The access to water will become an increasingly serious issue for unconventional gas development and power generation in parts of China and the United States, for India's increasing water-dependent power plants, and to Canadian oil sands production. This will require not only improving technology but also an integrated planning, taking both water quantity and water quality into consideration.

As a child I was told to turn off the light when leaving my room. Of course this will save energy. However, usually we are not aware that keeping our lamps burning and computers running will consume water. To keep my laptop running about 65 W is consumed. During a 12 hour period it has consumed water. If the power is coming from coal fired plants the computer will consume 1 liter of water and withdraw more than 100 liters for the thermal plant cooling and for the coal mining. Powering the laptop from a nuclear reactor will consume around 1.5 liter, while more than 200 liters of water is withdrawn for cooling (see Chapter 13). Hydropower actually can consume a lot of water due to evaporation in the reservoir. Depending on the location and design of the reservoir my computer may cause anywhere between 1 and 1000 liters of water to evaporate during the 12 hours (see Chapter 10). The surprising fact is that biofuel is not as green as many of us think. The water consumption to grow the crop and to extract the biofuel, such as ethanol or biodiesel will require a huge amount of water (Chapter 12). One liter of corn ethanol or soybean biodiesel may cause the consumption of more than 500 liters of water. If this water has to be pumped from groundwater sources to irrigate the crop then the biofuel is far from a sustainable source of energy. Furthermore, all the energy to grow the crop, refine the fuel and to pump the irrigation water has to be listed on the cost account for the fuel.

The first edition of this book used water-for-energy data from the World Energy Council report WEC (2010a). In the last few years there has been a tremendous development and water for energy has been the topic for a large number of reports. Personal experiences of international expert groups in water-for-energy and from guiding PhD students at various universities in Europe and Asia have motivated a renewed description of the area.

9

Water footprint of energy production and conversion

> *Water will be to the 21st century what oil was to the 20th.*
> Fortune Magazine 2000.

The world's primary energy sources are crude oil, liquid natural gas, natural gas, coal and electrical power from hydroelectric and nuclear power plants. Petroleum (crude oil and natural gas) continue to be the world's most important primary energy source. Coal ranks second as the primary energy source, while dry natural gas ranks third. Hydro, nuclear and other (geothermal, solar and wind) electric power generation ranks fourth, fifth and sixth respectively.

Concern about the impact on the environment of traditional methods of electrical power generation is driving the introduction of a variety of non-polluting, renewable energy sources. However, economies of scale on large thermal and hydropower plants as well as existing transmission/distribution grids plus government subsidies for these traditional systems put the renewable approaches at a cost disadvantage (Chapter 11.9). A wide range of renewable electricity production options is now available, together with a growing range of incentives and economic instruments to promote their use and also to promote increased efficiency of energy usage. Still the subsidies for new renewables are much less than those for the conventional fossil fuels.

As a sign of the magnitude of the water-for-energy issue the International Energy Agency's World Energy Outlook report 2012 included a special section on the water needs and the possible future water constraints of the energy sector (IEA, 2012). This is the first time the water need is analyzed in depth by IEA since the Outlook was first published in 1994. It is estimated (IEA, 2012, Chapter 17) that the total withdrawals of water in 2010 for energy production in the world were 583 billion (10^9) m^3 (bcm). This is about 15% of the total global withdrawals and corresponds to the annual discharge of the Ganges River in India, or some 19,000 m^3/second. Out of this some 11%, or 66 bcm were consumed. Around 90% of the total withdrawals, or 540 bcm, were used for electric power generation (see further Section 9.4 and Chapter 13). The United Nations World Water Development Report 2014 (UN WWDR, 2014) gives the same message.

It should be emphasized already here that saline or brackish water can be used instead of freshwater in many energy operations. Below we will describe this for oil, shale oil and oil sand operations (see also Chapter 11). Thermal power plants, located close to the sea will obviously use seawater for cooling (see Chapter 13). Even reused wastewater can be used in many energy operations.

> Energy requires water. The energy production sector uses more water from freshwater sources than any other sector except agriculture.

In the US the energy sector is the fastest growing water consuming sector. Energy production growth in the US alone is expected to require 165% increase in water use by 2025. The water withdrawal for energy is around 40% in the high-income countries. An average U.S. household's (2.4 persons) daily energy use (weighted by cooling technology and fuel mix) requires around 5 m^3 of water to be withdrawn. This is around five times more than the direct residential water use of that same household (Wilson *et al.* 2012).

In China, industry accounts for 25% of China's total water consumption and the largest portion of China's industrial water use is the energy sector. The water consumption for the production of coal accounts for about 20% of the water consumed. Hydropower also consumes water. There is a concern that many Chinese rivers will not be running in 2020 if China meets its stated goal of tripling hydropower capacity by 2020.

The energy sector also has an influence on water quality. Crude oil, natural gas, oil sands and oil shale extraction and water drainage from coal and uranium mining operations have a large impact on the water quality. Coal fired power plant emissions will have an effect on surface water quality.

Some sources of low-carbon renewable energy are the most water intensive. For example, corn ethanol made from irrigated crops can use 1000 times more water than oil refining (see Chapter 12). Also industrial concentrated solar arrays can require as much as 3000 liters of water to produce a single MWh.

Measuring the water footprint and ways to describe is considered in 9.1. Water quantity and water quality of one product has to be compared with the demand from another product or function. The global energy situation is then summarized in 9.2. Section 9.3 describes primary energy sources, the expected consumption in the next decades as well as the water requirements for primary energy extraction. Energy for the poorest part of the population is remarkably different from the high income parts of the world. In 9.4 electrical energy generation is discussed. Scenarios are shown for the next decades of electricity use and the impact on water resources. Section 9.5 discusses some of the constraints of water that the energy production has to face. The chapter is summarized in 9.6.

9.1 METRIC – MEASURING THE WATER FOOTPRINT

The water footprint – the amount of water consumed to produce a unit of energy (m^3/GJ which is the same as liters/MJ) – has been estimated by many different institutions and researchers. Mostly there is sufficient statistics and measurements in the industrialized countries and the assessments are more reliable for these countries. However, for the developing world it is much more difficult to obtain reliable data, since a relatively large fraction of the energy comes from biomass that is difficult to measure. Many rural areas are still heavily dependent on lumber and firewood for cooking.

Water consumption has to be measured both in terms of quantity and quality.

The *quantitative* measure of water consumed is just one aspect. The influence of the energy production and conversion on water *quality* is much more difficult to assess. Furthermore some assessment of other environmental and ecological factors also need to be measured, such as groundwater levels, water temperature, the need for artificial fertilizers, mortality of plants and animals, loss of biodiversity in breeding grounds, reduction in fishing and farming activity, impairment of human health, food insecurity and poverty, impairment of growth and reproductive outputs.

Energy Return on Water Invested – coined by Spreng (1988) and Voinov-Cardwell (2009) – has been used as an indicator to compare various methods of energy generation. For a given technology life cycle assessment (LCA) has been used to calculate the energy produced per unit of fresh water used (e.g., MJ/liter). However, things become complicated since water does not necessarily have to be consumed to produce energy. Much of the water withdrawn for energy production is returned back and can be reused. From a basin perspective, the only consumption occurs when water is either lost through evapotranspiration (in which case it may also reappear in the basin, but at a different place when rainfall occurs) or degraded through contamination that changes its chemical properties (such as toxic additions, including nutrients, pesticides, herbicides) or physical properties (such as water temperature, oxygen content), to such an extent that it is no longer usable.

9.1.1 International standard to measure the water footprint

To quantify how much water is needed to produce a product or to generate energy is of course an important task. This has been a crucial topic also in the definition of the UN Sustainable Development Goals and how to develop its agenda after 2015. The Sustainable Development Solutions Network (SDSN) was launched in August 2012 by the UN Secretary General Ban Ki-moon. The aim was to mobilize the scientific and technical expertise needed to accomplish the UN sustainability goals. In the SDSN ‘Action Agenda for Sustainable Development’ from 2013 there are ten objectives. One of them is to ‘Secure Ecosystem Services and Biodiversity, and Ensure Good Management of Water, Oceans, Forests, and Natural Resources’. One of the targets is to identify the percentage of total water resources used. Actually water use is integrated into several goals and the need for integrated management of freshwater resources has to be highlighted.

So, how much water are we using in our processes? The key issue is to define a consistent way to measure the water footprint. The ISO (International Organization for Standardization, www.iso.org) has more than 19,000 International Standards, and over 550 relate specifically to water. They tackle issues like service management of drinking and wastewater systems, water supply during crisis situations, irrigation, quality and conservation and infrastructure.

In July 2014 the ISO released a new standard that should bring a framework for measuring the potential environmental impact of water use and pollution, called ISO 14046, *Environmental Management – Water Footprint – Principles, Requirements and Guidelines.* A brief introduction is given at http://www.iso.org/iso/iso14046_briefing_note.pdf. More than 300 direct stakeholders carried out the ISO 14046 work over a period of over 5 years. Some of the organizations contributing to ISO’s water standards include WHO, WMO, FAO, OECD, IWA, Consumers International. The ISO 14046 standard is based on a lifecycle assessment and its purpose is to assist the users to:

- Assess the magnitude of potential environmental impacts related to water;
- Identify ways to reduce those impacts at various stages of a process, a product or an organization’s life cycle;

- Facilitate water efficiency and optimization of water management at product, process and organizational levels;
- Provide scientifically consistent and reliable information for reporting water footprint results that can be tracked over time.

The standard does not present a definitive definition for a water footprint but can provide a scientifically based definition to use and a standardized method for calculation. **A water footprint is not necessarily one single indicator**. Given the complexity of water-related issues, a water footprint is often more than a single number. The indicator that can be called a 'water footprint' is a set of indicators measuring the *reduced availability* of water and the *environmental impact* due to its pollution. The ISO standard provides a set of possible indicators to measure different issues, depending on the objective:

- water resources scarcity (indicator name: water scarcity footprint, see Glossary), and
- the reduction of available water due to pollution (indicator name: water availability footprint).

The ISO standard has been developed by a technical committee (TC) called ISO/TC 207/SC 5: Life cycle assessment.

There is a Water Footprint Network (WFN) method (see www.waterfootprint.org) that can be used to calculate the blue, green and grey water footprints (see the Glossary). The WFN can be seen as a complement to ISO 14046, but not entirely identical. The two methods don't have the same objectives. The WFN method has a much wider scope than ISO 14046 and has also a purpose to find solutions to reduce impacts.

It should be emphasized that the ISO standard does not define a methodology to assess a water footprint. Rather, it defines the requirements, guidelines and principles of it. For this reason, calculating a water footprint will require that a methodology is selected. The result of a water footprint assessment is a single value or a profile of impact indicator results. This is a challenge that is currently being addressed through an international working group called WULCA (Water Use in Life Cycle Assessment). The group was founded in August 2007 under the auspices of the UNEP/Society for Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative (see www.wulca-waterlca.org). The field of water footprint is quite new, even compared to the carbon footprint, so we can assume that methodologies will evolve in the coming years.

In this part of the book we emphasize water footprints for energy generation. There are also other interest groups that wish to find relevant measures of water footprints. Nine European organizations from five European countries have started the project URBAN_WFTP – 'Introduction of Water Footprint (WFTP) approach in urban area to monitor, evaluate and improve the water use' (www.urban-wftp.eu/en). This project in Central Europe emphasizes local water management in urban areas. The purpose is to integrate tools for monitoring and managing citizens' water use, water networks and wastewater treatment systems.

9.2 THE GLOBAL ENERGY

Primary energy sources come from fossil fuels, uranium, and potential energy in water (hydropower), and from various biofuels. Other still emerging sources are wind and direct solar power (solar PV or solar photo voltaics). Hydropower plants, thermal coal fired or nuclear power plants convert the energy from the primary sources to electrical energy.

9.2.1 Primary energy sources

Energy production and consumption worldwide increased drastically during the 1980s and slowed down somewhat in the 1990s. Petroleum production and consumption continues to increase, but whereas petroleum once constituted almost half the global energy it now accounts for less than 32%, Figure 9.1. Natural gas, coal and nuclear power have made up most of the difference. The total global annual energy use amounts to around 100,000 TWh. Out of this electricity amounts to around 22,000 TWh. This is divided between three sectors – transportation, industry and housing.

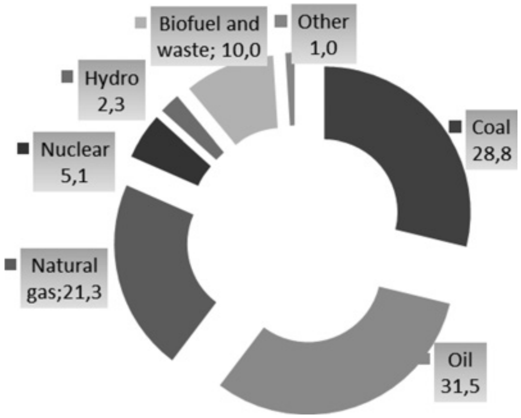


Figure 9.1 The share of different primary energy sources in the world in 2012. The category *other* includes geothermal, solar, wind, heat, and so on. (*Source:* IEA (2014c)).

The share of fossil fuels has increased from 80.9% in 2009 to 81.6% in 2011 (IEA, 2011, 2013b). The absolute numbers have also increased from a world total of 12,150 Mtoe to 13,113 Mtoe (for definition, see Appendix 1.2), so the fossil fuels have increased in two years from 9,829 Mtoe to 10,700 Mtoe or 8.9%. Coal has increased (from 27.2%), oil has decreased (from 32.8%), and natural gas has increased (from 20.9%). This is the sad development for climate change.

The share of fossil fuels in the world is more than 80% of primary energy sources.

The largest producers, exporters and importers of crude oil and of natural gas are listed in the Tables (9.1–9.2).

One third of the petroleum production comes from three countries: Saudi Arabia, Russia, and US. The US is by far the biggest oil consumer using more than 25% of the world's total. China, Japan, Russia and Germany are the next big consumers, but no nation consumes even half as much as the USA.

Transportation is the sector that has increased its energy uses the most, with a doubling of consumption since 1970. Vehicles in general have been more fuel efficient, but the total mileage has increased even faster.

Transportation has had the largest increase of energy use.

Table 9.1 The largest producers, net exporters and net importers of crude oil (production data from 2012, export and import data from 2011).

Producers	Mt*	% of world	Net exporters	Mt	Net importers	Mt
Saudi Arabia	544	13.1	Saudi Arabia	353	US	500
Russia	520	12.6	Russia	247	China	251
US	387	9.3	Iran	122	Japan	177
China	206	5.0	Nigeria	121	India	172
Iran	186	4.5	United Arab Emirates	114	Korea	125
Canada	182	4.4	Iraq	108	Germany	90
World	4,142	100	World total	1,982	World total	2,079

*Mt = million tons.
Source: IEA (2013b).

Table 9.2 The largest producers, net exporters and net importers of natural gas (2012).

Producers	bcm*	% of world	Net exporters	bcm	Net importers	bcm
US	681	19.8	Russia	185	Japan	122
Russia	656	19.1	Qatar	120	Germany	70
Qatar	160	4.7	Norway	109	Italy	68
Iran	158	4.6	Canada	57	Korea	48
Canada	157	4.6	Algeria	48	Turkey	45
Norway	115	3.3	Turkmenistan	37	US	43
World total	3,435	100	World total	282	World total	827

*bcm = 10^9 m^3.
Source: IEA (2013b).

The global energy use is also rising as a result of rising standards of living in the developing countries and of the increasing population. In the time it takes for the average fuel consumption per km to decrease by 50% the number of cars in the world doubles. And if we would manage to cut the energy use per capita the world's population will most likely increase to compensate for this. This leaves us in some status quo. In other words, to make energy use so efficient that the total use decreases is a gigantic challenge. Still the amount of fresh water required for generating all this energy remains the same.

The progress made by more efficient energy use is offset by continuously increasing needs.

Oil is still the world's most common energy source, even if its relative proportion is falling. Some sources claim that the world has already reached 'peak oil', which means that current extraction and consumption pace is higher than the pace at which new and economically accessible sources are being found. Oil will not cease to exist but will become more expensive and more difficult to extract. This implies more water use.

Fossil fuels will remain the dominating energy sources for decades ahead.

Coal is available in larger quantities than oil. With current extraction levels the world's accessible coal supplies are estimated to last for several hundred years. Even natural gas is available in enormous resources.

To make energy in fossil fuels useful to us, they must be burned in the engines of vehicles or in power plants producing electricity. There is a water price divided between extracting, transporting, enriching, and converting the energy of fossil fuels.

Early industrialization was based almost entirely on coal. The development of the internal combustion engine and the availability of oil caused oil to replace coal as the dominant fuel. The energy mix diversified further and today oil is dominating in transport while coal is still the largest primary fuel for power generation. Overall, the fuel mix remains determined by availability and the local cost of fuels.

9.2.2 Electrical energy

In 2011 more than 22,100 TWh of electrical energy was produced (and consumed) in the world (Figure 9.2), an increase of more than 10% in two years (IEA, 2011; IEA, 2013b). About 68% of this energy comes from coal, gas and oil fired power plants. Thermal power plants are driven by heat engines where steam drives a turbine and generator. They require water for cooling and include all the fossil fuel fired plants and the nuclear plants, together some 80% of all electric power generation. This explains why energy generation needs a lot of water.

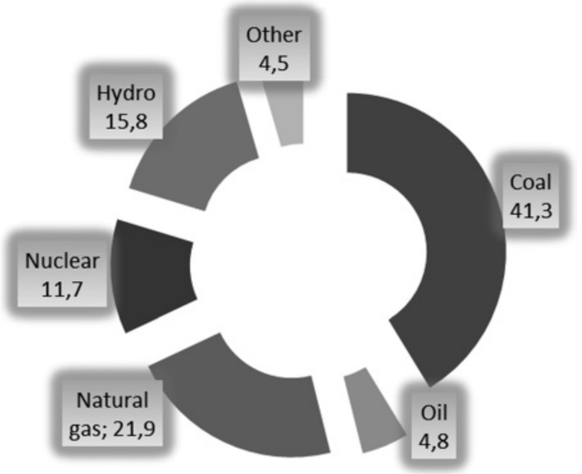


Figure 9.2 Estimated global electrical energy generation 2011 (total 22,126 TWh). (*Source:* IEA (2013b)).

The change compared to 2009 is not encouraging from a climate change point of view. Electrical energy from all the fossil fuels has increased: coal by 12.2%, oil by 3.9% and natural gas by 12.9%. Nuclear has decreased by 3.9%, which is partly related to the Fukushima Daiichi nuclear reactor disasters in March 2011 (see further Chapter 13). Hydro has increased 7.6% while the others (including geothermal, solar, wind, biofuels and waste) have increased more than 50%. However the new renewables still make up a very small part of the electric power production.

As Figure 9.2 illustrates coal and natural gas are the dominating fossil fuels for electrical energy. Together with nuclear energy they also present the largest challenges for cooling, which will be further discussed in Chapter 13. The largest producers of the various primary fuels are shown in Table 9.3. Whenever the coolant is fresh water there is a great water challenge in water scarce regions. This is true for western US, northern China, and many parts of India.

Table 9.3 The largest producers, net exporters and net importers of electrical energy (2011).

Producers	TWh	% of world	Net exporters	TWh	Net importers	TWh
China	4716	21.3	France	56	Italy	46
US	4327	19.6	Paraguay	46	US	37
Russia	1053	4.8	Canada	37	Brazil	36
India	1052	4.8	Russia	23	Finland	14
Japan	1043	4.7	Czech Rep.	17	Argentina	10
Canada	637	2.9	China	13	Netherlands	9
World	22,126	100	World total	282	World total	282

Source: IEA (2013b).

Table 9.4 summarizes the largest electric power producers using coal, natural and uranium, respectively. China is the dominating coal consumer, while the US leads both the natural gas and the nuclear power producers.

Table 9.4 The largest electricity producers using coal, oil and nuclear power (2011).

Coal/peat	TWh	Natural gas	TWh	Nuclear	TWh
China	3723	US	1045	US	821
US	1875	Russia	519	France	442
India	715	Japan	374	Russia	173
Japan	281	Iran	160	Korea	155
World total	9,144	World total	4,852	World total	2,584

Source: IEA (2013b).

The total electrical energy consumption corresponds to a global average of about 3,000 kWh/capita/year (Figure 9.3). While the OECD (countries from Europe, Americas and Asia-Oceania) countries can enjoy 8,200 kWh/capita/year the Africa average is only 600 kWh/capita. Canada with its almost 85,000 kWh/capita/year is not the biggest consumer. It lags far behind Qatar, the biggest energy consumer in the world, spending 207,000 kWh/capita/year.

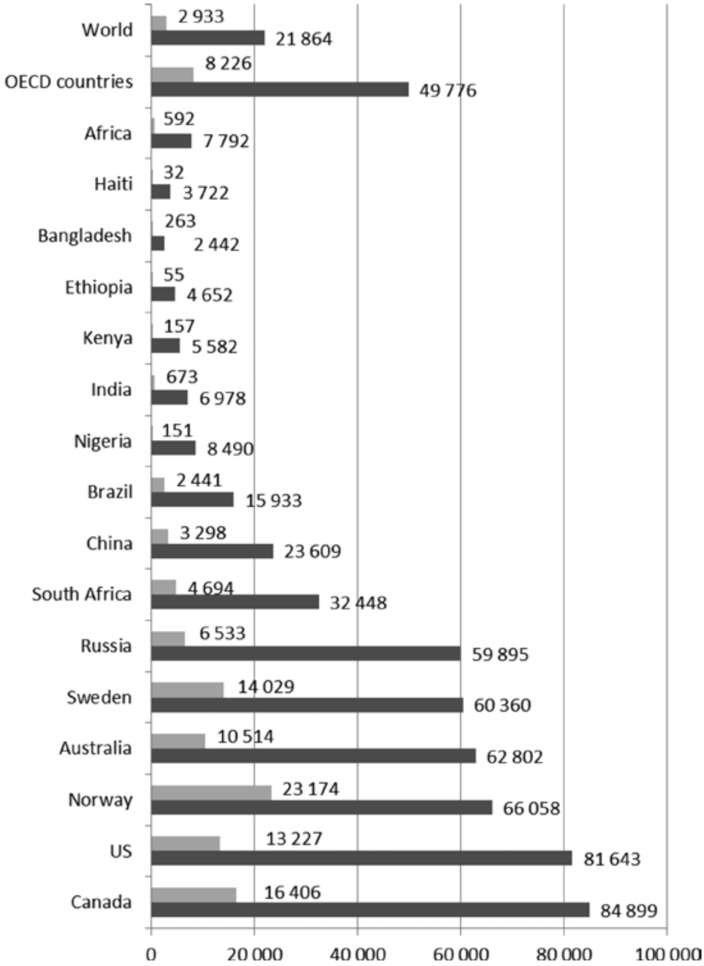


Figure 9.3 Comparison of the electrical energy consumption and the total primary energy supply in some countries. The upper (grey) bars indicate the electrical energy in kWh/capita/year and the lower (black) bar the total primary energy, expressed in kWh/capita/year. (*Data source:* IEA (2013b)).

The differences between individual countries are much wider than between the continental averages. As Figure 9.3 illustrates there is a disturbing and startling difference between the richest and the poorest, a more than 500-fold ratio. In Sub-Saharan Africa only 5–10% of the population have direct access to electricity and in rural areas only 2% have electricity. Energy poverty is one of the biggest obstacles to sustainable economic growth and development in many countries. Literacy, energy and water are truly basic conditions to rise out of poverty.

The richest countries consume more than 500 times more electrical power per capita than the poorest countries.

The ratio between the electrical energy consumption and the total supply is another aspect that is important to realize. For example, Norway uses much more electrical energy per capita than the US. The Norwegian ratio of electrical to total energy supply is 35% while it is only 16% in the US. Sweden, Australia and Norway use approximately the same amount of primary energy, while Sweden uses 23% for electric power and Australia only 16%. The reason is that electrical power is used for many more industrial and domestic operations in Norway and Sweden compared to US and Australia. Norway exports 98% of its oil and covers almost all its electrical energy needs with hydroelectric power. Sweden has no sources of fossil fuel and generates most of the electrical power with hydro and nuclear. In the US and in Australia, both having plenty of fossil fuel resources, much more coal, oil and natural gas is used to supply homes and industries with energy. Low-income countries like Haiti and Ethiopia use only about 1% of their primary energy for electric power. China uses 14% for electrical power while Russia uses only 11% for electricity generation.

The introduction of renewable energy sources – especially solar and wind energy – is causing a transition to more decentralized power supplies. The development of 'green' buildings stimulates not only decentralized power solutions but also decentralized water management solutions. At the same time it has to be realized that these sources are less predictable and more vulnerable. Therefore, one of the most important drivers to reduce the cost of energy is to minimize uncertainty and to improve the predictability and availability of wind and solar energy (see further Chapter 22.2). When it is not windy or when the sun is not shining other sources should be available. Small hydropower plants is another solution, see Chapter 10.4. This development generates a demand for 'off the grid solutions' for energy supply as well as water services. Although improving access to electricity is not one of the MDGs it plays a key role in reducing poverty, promoting economic activities and improving quality of life, health, and education opportunities, especially for women and children.

9.2.3 Energy for the poor

Worldwide 2.6 billion people rely on traditional biomass such as firewood, charcoal or crop residues for cooking, agro-processing and heating. They still need clean cooking facilities. Hundreds of millions of people have attained modern energy access over the last two decades, especially in China and India. Still, nearly 1.3 billion people lack access to electricity. Most of these people are in either developing Asia or sub-Saharan Africa, and in rural areas. Just ten countries account for two-thirds of those without electricity and just three countries – India, China and Bangladesh – account for more than half of those without clean cooking facilities (IEA, 2012). The number of people not having access to electricity decreased by 50 million between 2010 and 2012, while the amount of people relying on traditional biomass did not decrease. So, with this rate of change it will take a very long time to provide the poorest people with clean cooking facilities.

There are also around 400 million people that rely on coal for cooking and heating purposes, which causes air pollution and has serious potential health implications when used in traditional stoves. These people are mainly in China, but there are also significant numbers in South Africa and India.

The prevailing view of the almost 3 billion people that rely on primitive biomass or coal is: 'If there is no fire in the house, it is not a house'. Women and children have the heaviest burden to collect both firewood and water. Devastating illness results. More than 4 million people die each year from the effects of the indoor smoke, representing the world's fourth-leading cause of death.

Biomass is the poor man's main energy source.

The population in the developing world will increase from about 5.3 billion today to about 6.6 billion. This will put a tremendous pressure on the development. IEA predicts that some 1.6 billion will get access to electricity. Still, this means that even in 2030 almost 1 billion people will lack electricity.

There are certainly a number of new initiatives to increase access to electricity or lighting across various regions. The United Nations designation of 2012 as the Year of Sustainable Energy for All, coupled with the decision by the UN Secretary-General to include universal access to modern energy within his Sustainable Energy for All initiative (SE4All), set the tone. The programs include the Global Lighting and Energy Access Partnership (Global LEAP), D.Light Design, Energising Development programme, and Lighting India (IEA, 2012). The SE4All initiative also included access to clean cooking facilities. In 2010 the Global Alliance for Clean Cookstoves was launched.

In Africa, 57% of the population has no access to electricity, and 68% use traditional biomass for cooking. Corresponding numbers in developing Asia is 18% and 51% respectively (IEA, 2012, Chapter 18). Indoor air pollution from the burning of traditional biomass is a major cause of ill health, particularly among women and children.

The number of people without clean cooking facilities is projected by IEA (2012) to remain almost unchanged until 2030, continuing at around 2.6 billion in 2030 – more than 30% of the global population at that time. Still it is predicted that around US$635 million per year until 2030 will be invested in clean cooking facilities.

IEA has also analyzed what would be needed to reach the goal that all people should have access to electricity and clean cooking facilities by 2030. The total investment of nearly US$ 1 trillion (10^{12}) would be required or an average of around US$ 50 billion per year from 2011 to 2030. This requirement corresponds to around 6% of the global energy related infrastructure investments (see Section 9.4), or about US$ 30 per person and year among the richest 1.5 billion people of the world to the developing world. Various pathways to achieve these goals are described in Chapter 17 of GEA (2012). Impossible? To provide just clean cooking for all needs less than US$ 4 billion per year. This would provide clean cooking facilities to an additional 135 million people per year on average, through a combination of advanced biomass cook stoves, LPG (Light petroleum products such as liquefied petroleum gas (LPG), naphtha and gasoline) stoves and biogas systems. This corresponds to US$ 30 per stove.

By investing around 6% of what the high income countries will invest in energy systems 2.6 billion people would obtain electricity and clean cooking facilities by 2030.

There is a close relationship between energy and food poverty, and women illiteracy and infant mortality. Everyone has the right to enjoy a decent standard of living and standard of energy. Finding solutions to meet these needs must be our first order priority.

9.2.4 Energy subsidies

Great subsidies are given today to promote energy consumption. The rationale for subsidies looks well-intended, like alleviating poverty and promoting economic development. The global subsidies for fossil fuels (oil, natural gas and electricity) in 2011 were US$ 523 billion (10^9). This is an increase from US$ 409 billion in 2010 and US$ 300 billion since 2009 (IEA, 2011; IEA, 2012, Chapter 2). Fossil fuels were subsidised at a weighted-average rate of 24% in 2011 in the economies identified, meaning that consumers paid only 76% of the reference or subsidized price, based on international prices.

The fossil fuel subsidies in 2011 were 6 times larger than subsidies to renewable energy. Renewable-energy subsidies were $88 billion in 2011 but need to reach US$ 240 billion by 2035. Renewable energy is subsidized in order to compete in the market, increase their volume and develop the technology so that the subsidies become unnecessary with the development.

> *Subsidies for fossil fuels are more than six times larger than for renewable energy*

Energy subsidies may be direct cash transfers to producers or consumers as well as indirect support mechanisms, such as tax exemptions and rebates, price controls, trade restrictions, and limits on market access. Most of the subsidies were given by fossil fuel exporters. This will speed up the depletion of the resources and will reduce the export incomes in the long time perspective. For the importers the subsidies often impose a large burden on the state budgets. The subsidies are inefficient means to help the poor part of the population. Only 8% of the US$ 409 billion subsidies in 2010 were received by the poorest 20% of the population (IEA, 2011).

Subsidies can have a lot of unintended consequences and often result in inefficient allocation of resources. According to IEA (2011) some of the consequences are:

- Encouragement of wasteful consumption;
- Speeding up the decline of exports;
- Encouragement of smuggling and adulteration;
- Disproportional benefits to middle class and rich;
- Drain state budgets for imports;
- Create barriers to clean energy development;
- Dampen the response to high prices;
- Increase the CO_2 emissions.

I often travel between Singapore and Malaysia and get a reminder about subsidies. The gasoline prices are about twice as high in Singapore compared to Malaysia, so it would be very tempting to drive over to Malaysia to buy the gasoline. However, a driver exiting Singapore with less than 75% gasoline in the tank will risk a stiff penalty.

It is getting recognized that phasing out the subsidies will bring many benefits, both economic and environmental. The growth in energy demand should be reduced, and the CO_2 emissions can be cut. Phasing out fossil-fuel subsidies by 2020 would cut primary energy demand 5%, according to IEA. Many countries have started or planned reforms since 2010. Both the G20 countries and the Asia-Pacific Economic Cooperation (APEC) agreed in 2009 to phase out the subsidies for fossil fuels (so far the result is not encouraging, see Chapter 11.9). A lot of reforms have to be done to realize the full extent of the benefits. In the IEA New Policies Scenario, they are assumed to be phased out by 2020 at the latest. IEA predicts that onshore wind may become competitive around 2020 in the European Union.

9.3 PRIMARY ENERGY SOURCES

We will consider the predicted global production of various sources of energy and then discuss the demand of water to extract and refine these sources. There are various scenarios of the future demand for energy as well as for water for energy. Here we present two of them, developed by IEA and by the World Energy Council.

9.3.1 Primary energy production predictions

IEA has formulated The *New Policies Scenario* that is the central scenario of the IEA's world energy model. This scenario takes into account broad policy commitments and plans that have been announced, even where the specific measures to implement these commitments have yet to be introduced, in addition to those that have already been implemented to address energy-related challenges. We will use this as the data background for the power predictions and water needs predictions until 2030.

The global production of primary energy sources is expected to increase from about 530 EJ (10^{18} J) in 2010 to about 720 EJ in 2030, an increase of 35% (Converted from Table 2.2 in IEA, 2012). Crude oil, natural gas and coal are the dominating primary energy sources in the world today. As shown in Table 9.5 they will still remain the dominating primary sources in 2035, according to various predictions. As a comparison we also show the predictions made by the World Energy Council (WEC, 2010a).

Table 9.5 Prediction of the energy demand according to the IEA New Policies Scenario and the World Energy Council (WEC).

Energy demand (EJ)	World total	Coal	Oil	Gas	Nuclear	Hydro	Bioenergy	Other renewables
2010 (IEA)	533	145	172	115	30	12	53	4.7
2035 (IEA)	720	175	192	160	45	19	73	23
2035 (WEC)	668	170	187	169	51			

Source: IEA: Converted from IEA (2012), Annex A and from WEC (2010a).

The percentage of respective primary energy sources are shown in Figure 9.4. The shares of coal and oil will decrease over the 25 year period, while gas, hydro, nuclear and bioenergy are expected to increase their share. The biggest increase will take place for other renewables, and still their share in 2035 will be just 4%. In 2011 the world oil production was 3,995 million tons. The majority was conventional (crude) oil, some 95%. Only 5% was un-conventional oil, such as the Canadian oil sand and heavy oil from the Venezuela Faja del Orinoco deposit. The non-conventional share of oil will increase significantly over the next decades, see below.

It is obvious that the demand for all energy sources will increase and the fossil fuels will still be dominating, from 81% in 2010 to 77% in 2030. The rates of increase, however, are quite different, as depicted in Figure 9.5.

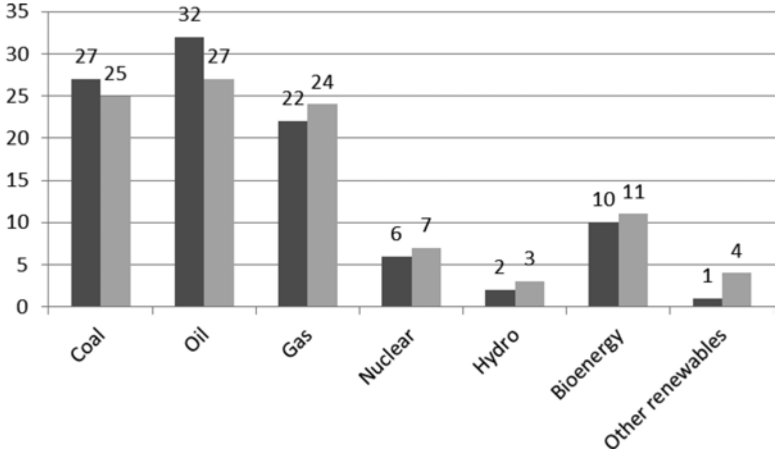


Figure 9.4 Demand for various primary energy sources in % of total. The left bar was the situation in 2010 and the right bar is the predicted value for 2035. (*Source:* IEA (2012), Annex A).

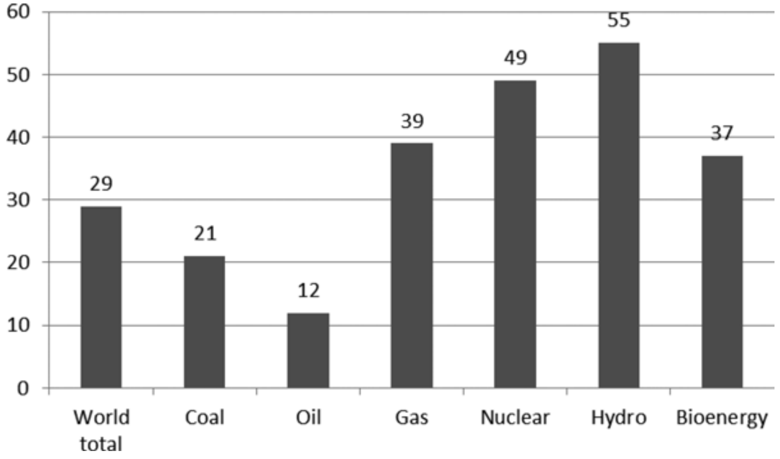


Figure 9.5 Increases in primary energy use (%) from 2010 to 2030 according to the New Policies Scenario. New renewables will have a more than 500% increase. (*Source:* Converted from IEA (2012), Annex A).

Energy from coal production is presently below oil but will likely become higher over the next 25 years, as noted in Table 9.5. The increase in oil is mostly due to increasing production of non-conventional oil. Coal and oil will not grow as much as other energy sources. The great increase in gas production is related to the 'revolution' in shale gas production, made possible by horizontal drilling technology in combination with hydraulic fracturing (Chapter 11.2). It is noticeable that nuclear power is expected to grow significantly, also according to the International Atomic Energy Agency (IAEA, 2014). The growth of hydropower is a great concern from a water use point of view, which is further discussed in Chapter

10. Also bioenergy will grow, and this will have a great influence on water use as well as demanding land use, in competition with food production (Chapter 12). The five-fold increase in renewables is of course a huge development. Still these power sources will provide only 3–4% of the total energy needs.

Biomass plays an important role in meeting energy demand in many regions in the world. Considered as the fuel for the poor, it plays a crucial role especially in the energy mix of developing countries. Biomass used in small-scale appliances (typically ≪1 MW) is rather inefficient and highly polluting, as noted in Section 9.1. The statistics on biomass in the developing world is quite incomplete. It has been assumed that traditional biomass use may add some 10% to the global energy consumption.

There are several predictions and projections made for the future energy demand, such as EIA (2014), IEA (2013a) and BP Energy Outlook (2014). According to the BP report the primary energy demand will increase by 41% between 2012 and 2035, or 1.5% per year. However, the growth is slowing down, from 2.2%/year for 2005–15, to 1.7%/year in 2015–2025, and only 1.1%/year in 2025–2035. Most of the energy growth, 95%, will take place in non-OECD countries, which means 2.3%/year at an average, while the energy growth in OECD countries will be just 0.2%/year in 2012–2035. It is predicted that the energy consumption in the OECD countries will decrease after 2030. The predictions by IEA and by BP are compared in Figure 9.6.

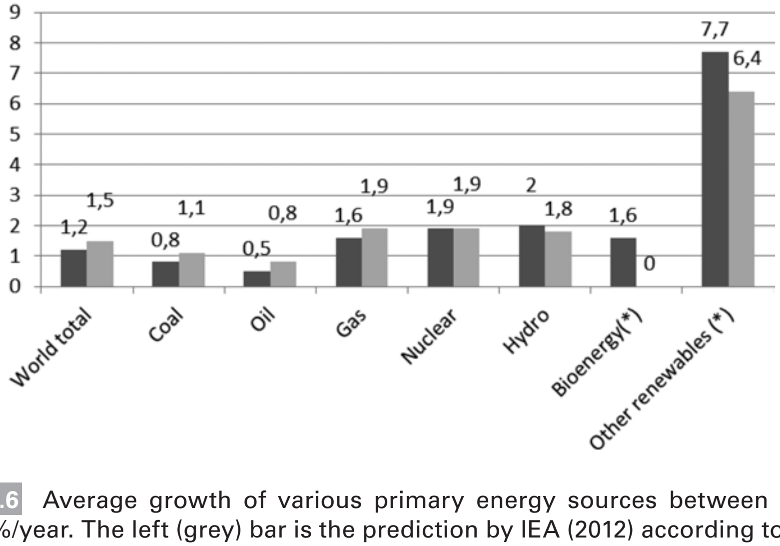


Figure 9.6 Average growth of various primary energy sources between 2012 and 2035 in %/year. The left (grey) bar is the prediction by IEA (2012) according to the New Policies Scenario. The right (black) bar is the estimated made by BP Energy outlook (2014). (*) Renewables for BP include biofuel but exclude hydropower.

China has emerged as the key growth contributor, but by the 2030s China's energy growth will decrease. India's energy demand will grow fast and in the final decade the growth rate in India will almost match that of China. Coal's contribution to growth diminishes rapidly. It is currently the largest source of volume growth, but by the final decade coal adds less volume than oil and is only just ahead of hydro. Again, this reflects the shift away from coal-intensive industrialization in China. In that final decade, gas is the largest single contributor to growth; but non-fossil fuels in aggregate contribute even more than gas, accounting for 39% of the growth in energy in that period.

Fuel shares evolve slowly:

- Fossil fuels will lose share but they are still the dominant form of energy in 2035, according to both IEA and to BP (see also Chapter 4.2). There is a difference in the IEA and BP prediction. An important reason for the difference is that the BP energy outlook is based on a 'most likely' assessment of future policy trends. The IEA energy projections are based on specific policy scenarios and make no judgments about the likelihood of those scenarios.
- Oil's share continues to decline, its position as the leading fuel briefly challenged by coal.
- Gas gains share steadily.
- By 2035 oil, gas and coal will have about the same share of the fossil fuel. For the first time since the Industrial Revolution there is no single dominant fuel.
- Nuclear and hydro remain fairly small parts of the total energy.
- Renewables (including biofuels) gain share rapidly. Around 2025 they are expected to overtake nuclear, and by 2035 they can match hydro.

Fossil fuels will lose share but are still the dominant form of energy in 2035

In 2012, 42% of the world primary energy was converted to electrical power, up from 30% in 1965 (BP energy outlook, 2014). It is expected that the share will rise to 46% in 2035. At a global level coal will remain the largest source of power for electric power generation even in 2035, even if gas will overtake the coal in the OECD countries. The dominating climate challenge is that the carbon emissions will continue to grow, only slightly slower than the energy consumption as the energy mix gradually decarbonises. Still the global emissions in 2035 will be nearly twice as large as the 1990 level.

Industry accounts for more than half of the growth of energy consumption (most as electrical power) 2012–35. This reflects the pace and scale of industrialization in Asia. The transport sector continues to play a relatively small role in primary energy growth throughout the forecast, growing steadily but accounting for just 13% of total growth during 2012–35 (BP energy outlook, 2014).

There will be a clear decoupling between energy consumption and economy measured in GDP. This means that energy required per unit of GDP is actually expected to decline by 36% between 2012 and 2035 (BP energy outlook, 2014), in other words more value can be created with less energy.

9.3.2 Water requirements to produce the primary energy

The type of water requirements to extract, produce, refine and transport primary energy are summarized in Table 9.6.

Almost all kinds of energy extraction require water.

In describing water for energy we will discuss the water intensity which is defined as the amount of water that is withdrawn or consumed divided by the energy that is produced. This can be quantified in terms of liters/kWh (the same as m^3/MWh) or m^3/GJ and so on. To make the numbers more understandable we will try to translate this into liters of water required to produce one liter or kg of the fuel. Table 9.7 summarizes the water consumption for primary energy production of fossil fuels. The water need for biofuels is discussed in Chapter 12. Any water used in the oil operations will require substantial treatment before it is released. Therefore it is reasonable to consider the consumption as the same as the withdrawal of water.

Table 9.6 Water requirements for primary energy production.

	Energy element	Water quantity	Water quality
Energy extraction & production	Oil and gas exploration	Water for drilling, completion and fracturing	Shallow groundwater quality impacted
	Oil and gas production	Large volume of produced impaired water	Produced water can impact surface and groundwater
	Coal and uranium mining	Large quantities of water may be used	Tailings and drainage can impact surface water and groundwater
Refining and processing	Traditional oil & gas refining	Water needed to refine oil and gas	End use can impact water quality
	Biofuels and ethanol	Water for growing and refining	Refinery wastewater treatment
	Synfuels and hydrogen	Water for synthesis or steam reforming	Wastewater treatment
Energy transportation & storage	Energy pipelines	Water for hydrostatic testing	Wastewater requiring treatment
	Coal slurry pipelines	Water for slurry transport; water not returned	Final water is of poor quality; requires treatment
	Barge transport of energy	Fuel delivery impacted by river flows and stages	Spills or accidents can impact water quality
	Oil and gas storage caverns	Large quantities of water required for slurry mining of caverns	Slurry disposal impacts water quality and ecology

Source: DOE (2006), Table II-1.

The worldwide global average of water demand for fossil fuels looks very small, only some 0.5% of all withdrawals. Obviously this does not consider the water quality impact. Furthermore, the regional variations are huge. Naturally the impact on water is massive in arid regions. 85% of the water used for fossil fuels is consumed in coal and conventional oil production (Williams-Simmons, 2013).

The table shows great differences between the sources. One explanation for the difference is that the data can indicate either freshwater or total water consumption. The majority of the water being used in the operation (called produced water) can be re-injected, and then the need for supplemental freshwater will be less. According to Williams-Simmons (2013) the volume of water required for crude oil operations is roughly the same as the volume of water. Furthermore, the water can also be seawater or brackish water.

- *Conventional natural gas:* the actual water required to extract natural gas (conventional) is low compared to other energy carriers (Table 9.7). Conventional natural gas (that consists of 90–95% methane) is the fossil fuel with the lowest carbon emission (see Chapter 11). In total the production of natural gas accounts for less than 0.5% of total water consumption in energy production.

Table 9.7 Water consumption for primary energy production of fossil fuels.

Energy source	Liters/MJ (liters/toe)	Energy content (App. A2)	Liters of water per kg (gas) or liter of fuel (liquid)
Conventional gas	0–0.010[a] (0–436) 0.11[b]	55 MJ/kg	0–0.55[a] 5.9[b]
Coal	0.004–0.052[a] (151–2187) 0.16[b] 0.005[d] 0.002–61[e]	25 MJ/kg[3]	0.10–1.3[a] 4.0[b] 0.13[d] 0.05–1600[e]
Shale gas	0.002–0.114[a] (87–4786)	55 MJ/kg	0.11–6.3[a] 0.3[c] 3–17[c,5]
Refined oil – conventional[1,4]	0.005–0.072[a] (209–3020) 1.06[b] 0.005–0.026[c]	37 MJ/liter	0.18–2.7[a] 39[b] 0.2–1[c]
Refined oil – oil sands[2]	0.083–0.315[a] (3467–13,182) 2.6–4.2[b]	37 MJ/liter	3.1–11.6[a] 96–155[b] 4[c]
Refined oil – EOR	0.14–0.477[a] (6025–19,952)	37 MJ/liter	5.3–17.6[a]

[1] The minimum is for primary recovery; the maximum is for secondary recovery.
[2] The minimum is for in situ production; the maximum is for surface mining.
[3] Estimated average of various coal qualities.
[4] The freshwater is used for on-shore oil extraction. Off shore oil production primarily uses seawater.
[5] US values.
[a] Converted from IEA (2012), Figure 17.3.
[b] From WEC (2010a).
[c] Williams-Simmons (2013).
[d] Williams-Simmons (2013), average for Australia.
[e] Williams-Simmons (2013), average for China.
The consumptions are given for extraction, processing and transport. Data converted from IEA (2012), Figure 17.3; US DOE (2006); Gleick (1994); World Energy Council (WEC, 2010a).

- *Shale gas* is considered a non-conventional gas (see Chapter 11). The natural gas production in the world was 2,800 billion m^3 in 2010. Conventional natural gas is still the biggest part of the gas, around 86%. Shale gas is today 4.4% but its share is rapidly increasing. Water is used in hydraulic fracturing to extract the shale gas. This is a technique that is used to pump fluid (80% water) into the shale formations at high pressure to crack the rock and release the gas. Water requirement is site specific and depends on gas recovery rates, the number of hydraulic fracturing treatments and the extent of water recycling. Typically the water requirements are many times greater than for conventional gas. The concerns of water contamination are also further discussed in Chapter 11.

  The data for shale gas are very uncertain. One reason is that the water for fracturing is consumed at the beginning of the operations, while the full energy content from the shale gas produced in the well will only be known after a long time of gas extraction. Therefore the data are often based on estimates of the ultimate production from the wells. Water demand for shale gas fracturing ranges from about 11,000 to 35,000 m^3 per well (see further Chapter 11.2). The requirement for freshwater can be reduced by recycling produced water or using brackish water.

- *Coal:* Coal production requires water mainly for mining, which includes washing and beneficiation (Chapter 11.8). The amount of water used is site specific, for example if the mine is surface or underground. Power plant use of coal will increasingly demand coal washing. It will raise the quality of the coal and increase the plant efficiency. The runoff from mining operations can cause major pollution in surface water and groundwater. Overall the production of coal accounts for about 1% of total water consumption in energy production.

  For coal operations the consumption depends both on availability and on local regulations. Recycled water can be used for some mining operations. The consumption also varies with the amount of coal washing. In water scarce and warm areas the evaporation from stored water can be substantial (see the discussion in Chapter 10.2).

  For example, in China most coal mines have severe water shortage problems. In some parts of China, 30 years ago the water table was 5 m below the ground. Today it is 35–40 m below the ground because the groundwater is used in an unsustainable way.

  China has announced that it needs to curb coal-to-liquid (CTL) production, because of concerns over pollution and the volumes of water consumed (Circle of Blue, 2011, 2013). The water consumption is estimated to 10–12 liters of water per kg of coal (compare Table 9.7). Nevertheless more recently it was announced that the facility 'will start operating later this year (2014) and is expected to convert 3.5 million tons of coal per year into 1 million tons of oil products such as diesel for cars.' They will use groundwater and recycled water from coal mines to supply the 8 million tonnes it will need each year.

- *Oil*: the water requirements for crude oil extraction are relatively small compared to other primary fuels and depend on the extraction technique used and the geology of the oil field. The initial extraction of oil and gas requires less consumption of water, but, as oil wells age, enhanced oil recovery (EOR) techniques are used to extract additional oil. This can have water needs that are about ten times those for the initial extraction (see Chapter 11.1). The water consumption for the production of oil is today 10% of the total water requirement for primary energy production.

- *Nonconventional oil*: this includes oil sand and consumes significantly more water than processing conventional oil. For oil sand operations (see further Chapter 11.7) more water is needed for mining operations than for in situ operations. Some 20% of the oil is extracted from in situ mining. The freshwater use in oil sand has decreased and has been replaced by increasing recycling rates and treated brackish or saline water. The Canadian Association of Petroleum Producers (2014) report that recycling and reuse reached 90% in the Alberta oil sand operations.

Also the extraction of nuclear reactor primary fuel, uranium, requires water, but much less water per energy unit. Mining, milling as well as the conversion and processing of uranium requires less water per energy unit than anything else. It is estimated that approximately 0.09 liters/MJ is needed (compare Table 9.7). Considering the huge energy content (theoretically it is of the order 80×10^6 MJ/kg) the water consumption for nuclear energy production is low, less than 0.2% of total water consumption in all energy production.

9.3.3 Predictions of water requirements

In the New Policies Scenario, published by IEA (2012), it is predicted that the global water withdrawals will increase around 20% by 2035, compared to 2010. If the current trends ('business as usual') would continue then the water withdrawals in the same period would increase by 35%. However, the energy related water consumption is expected to rise even more, some 85% in the New Policies Scenario and some 100% in the 'business as usual' scenario. One reason for this is that once-through cooling will decrease and be replaced by closed loop wet-tower cooling (see further Chapter 13). Another reason for less water requirement in the New Policies scenario is that renewables, such as wind and solar PV, will have an expanded role, thus reducing the water withdrawals.

The IEA predictions based on the New Policies Scenario (IEA, 2012, Chapter 17) are summarized in Table 9.8. Freshwater requirements are quantified for the production of primary fuels (oil, gas, coal and biomass) consumed in all end-use sectors and for all forms of electricity generation, excluding hydropower.

Table 9.8 Prediction of the global water-for-energy demand (in billion m^3) according to the IEA New Policies Scenario.

Year	Water withdrawals	Water consumption
2010	583	66
2020	682	95
2035	691	122

Data from IEA (2012), Table 17.4.

We note that the increase of withdrawals is about 17% in the first ten year period and then is dampened to a very small increase. A change in cooling water technologies from once-through cooling to wet-tower cooling is a major factor (see further Chapter 13.2). The water consumption, however, will increase by almost 44% for the first 10 years and another 28% in the last 15 year period. So, the total consumption in the 25 year period is expected to increase by 85%. A major reason is that replacing the once-through cooling will increase the consumption, even if the withdrawals are decreased. Still, in a 'business-as-usual' scenario the water consumption would double.

The total energy related water consumption is expected to increase by 85% in the next 25 years.

It is obvious that water requirements to support future energy production vary by scenario. They predict different trends in energy demand. A major influence in the water withdrawal is related to the water withdrawal for cooling of thermal power plants (see below) as well as the rate of production growth for biofuels. There is a general trend across the scenarios toward higher water *consumption* by the energy sector over 2010–2035, while the trend of *withdrawals* is more variable.

The World Energy council has estimated the total water demand for energy use and the key results are presented in Table 9.9. It is apparent that the estimates are widely different from the ones presented by IEA and different uses, such as traditional biomass, are reported differently.

Table 9.9 Prediction of the water-for-energy demand (in billion m^3) according to the World Energy Council (WEC, 2010a).

Year	World total	Coal	Oil conventional	Oil non-conventional	Gas	Nuclear (uranium)	Trad. biomass
2005	1775	20	167	13	11	2.5	1562
2020	1930	24	164	83	15	2.9	1641
2035	2012	28	143	178	18	4.4	1640

Note that traditional biomass requires most of the water, primarily via irrigation. Its share of water resources will decline a little, from 88% in 2005 to 82% in 2035. Still biomass accounts for only about 10% of total primary energy production. In 2050 it is expected that the share of biomass in the total primary energy production will diminish to less than 5% (WEC, 2010a). More discussion of biomass is found in Chapter 12.

As illustrated in Figure 9.7 there will be a significant increase of water for primary energy source extraction. Comparing the two 15 year time intervals there will be a damping in the water requirements in the second 15 years period compared to the first 15 year period, except for the nuclear power. The latter indicates the water need for uranium extraction. Cooling of nuclear reactor plants is commented later.

Canada oil sand: Although Canada is a water-rich country, with annual per capita renewable water resources in excess of 85,000 cubic metres, extensive use of water in the extraction and upgrading of oil sands (or bitumen) in parts of Alberta and Saskatchewan provinces.

Oil sands production has grown from 0.6 million barrels per day (mb/d) in 2000 to 1.6 mb/d in 2011 and is projected to increase to 4.3 mb/d in 2035 in the New Policies Scenario, making an important contribution to global oil supply and energy security (IEA, 2012, Chapter 3). It is estimated (compare Table 9.7) that mining (plus upgrading) requires 5.7 m^3 of water per m^3 of synthetic crude oil produced while in-situ recovery requires 1.25 m^3 of water per m^3 produced. Based on expected production trends it is predicted that water withdrawals for oil sands – including fresh and saline sources – will grow from about 220 million m^3 in 2010 to about 520 million m^3 in 2035.

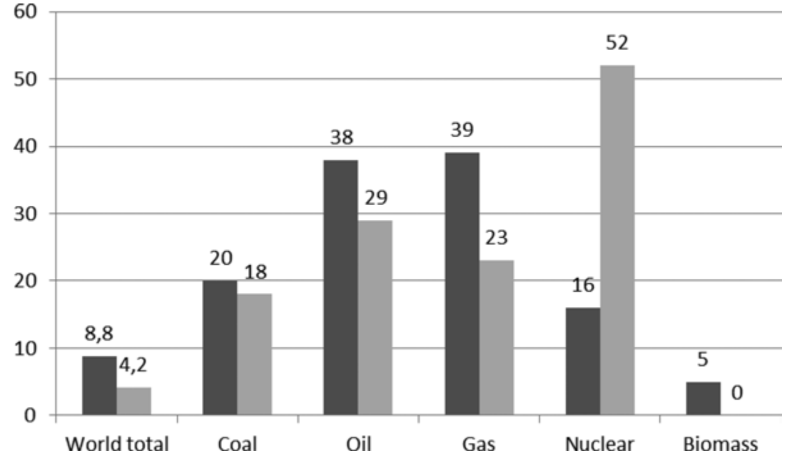


Figure 9.7 The increase (%) of water use for primary energy extraction over the two 15 year periods 2005–2020 (left bar) and 2020–2035 (right bar), respectively. The oil growth reflects the combination of conventional and non-conventional oil. While the water need for crude oil will decrease (Table 9.9) the water need for non-conventional shows a dramatic increase of 640% over the first 15 year period and another 215% over the last 15 year period. (*Source of data*: World Energy Council (WEC, 2010a)).

> The impact of oil sands' production on water quality is a critical issue. The discharge of untreated wastewater into rivers is prohibited, but there is concern that seepage from the vast tailing ponds already used to store degraded water could cause surface and groundwater pollution (see Section 11.7). For the protection of ecosystems, regulations mandate that rigorous monitoring is performed and prevention systems are in place to guard against seepage.

A calculation of UNESCO-IHE is worth citing. The present total annual energy use in western societies of about 100 GJ (corresponding to about 28,000 kWh) per capita is generated with a mix of primary energy carriers, requiring about 35 m^3 of freshwater per capita (or 100 liters/capita/day).

The present total energy use in western societies requires about 100 liters of water per day and per capita.

If the same amount of energy were to be generated from biomass only, it would require – even if it were to be produced in a highly productive agricultural system and under climatic conditions such as in the Netherlands – 2400 m^3 of freshwater, about 70 times higher than generating energy from other primary energy sources. Besides the disproportional amount of water needed to produce biomass, using biomass to generate energy is not in all cases emitting less greenhouse gases. Therefore, it seems to be highly questionable whether the

Energy generated from biomass requires significantly more water for the extraction than other energy sources.

Wind and solar energy (photo-voltaic) are considered to have the lowest water footprint. However, they are considered to have a large land use footprint, since the energy generated per m^2 is low, compared to other energy sources. This statement is challenged in Chapter 22.2. It should be emphasized that the capacity planning has to be made with probabilistic methods, since the generation cannot be guaranteed at all occasions. These energy sources must be complemented with other sources, such as hydropower, to provide the base load or to compensate for variable production. As a consequence the wind and PV technologies may not be considered water neutral. Wind and wave power can have other interesting applications, such as providing power for desalination (Chapter 20.8, 22.2).

9.4 ELECTRICAL POWER GENERATION

The global demand for electrical power will grow faster than the demand for any other form of energy. It is critical for most society functions and we know by experience that a blackout of electrical power will completely paralyse the modern society.

9.4.1 Predictions of electrical energy use

The use of electrical energy in the world and in some key regions is summarized in Table 9.10 and shows the expected development over the next 25 years, according to IEA New Policies Scenario (IEA, 2012).

Table 9.10 Electrical power demand (TWh) in key regions in the world.

Year	World total	United States	Europe	China	India	Africa
2010	18,443	3,893	3,232	3,668	693	569
2035	31,859	4,769	3,938	8,810	2,463	1,195
% increase	73	22	22	140	355	110

Source of data: IEA (2012), Table 6.1.

Later estimates of the global electrical energy demand (IEA, 2014c) is 19,560 TWh in 2012 (a 6% increase in 2 years) to 34,900 TWh in 2040, indicating an average growth of 2.1% per year for the next three decades. It is obvious that the major growth of electric energy demand will take place in Asia. China alone will be responsible for 38% of the global growth, while India will contribute with 13%. Already in 2011 China overtook the US to become the largest electric energy consumer in the world. Still the electric energy demand in India will grow faster than in any other region in the world.

In Figure 9.3 we illustrated the huge difference between different regions of the per capita electricity demand. The per capita demand in the OECD countries is far higher than the non-OECD and was 7,800 kWh in 2010 and will grow to 8,700 kWh in 2035, a growth of 11.5%. The non-OECD per capita demand is growing faster but from a much lower level, from 1,600 kWh in 2010 to 2,800 kWh in 2035, an increase of 75%. The sub-Saharan Africa will still be so much less privileged and even in 2035 the per capita consumption will be only 500 kWh.

Globally, the number of people with access to electricity worldwide will increase significantly. In 2010 some 19% of the world population lacked electricity and still, in 2030 some 12% of the population will lack access to electricity.

The fuel mix for electric power generation is summarized in Table 9.11. As remarked already in Table 9.5 the use of fossil fuels will still be the dominating source of power in 2035.

Table 9.11 Prediction of the electrical energy demand (TWh) according to the IEA New Policies Scenario and the World Energy Council (WEC). Notice the differences between Tables 9.10 and 9.11 in the World Total, reflecting different numbers reported by IEA.

Electric power demand (TWh)	World total	Fossil fuels[a]	Nuclear	Hydro	Other renewables
2010 (IEA)	21,408	14,446	2,756	3,431	775
2035 (IEA)	36,637	20,929	4,366	5,677	5,665
% increase (IEA)	71	45	58	65	730
2035 (WEC)	39,071	22,492	5,423	4,956	3,910

[a] Includes coal, gas and oil.

Sources: IEA (2012), Chapter 6; World Energy Council (WEC, 2010a).

It should be emphasized that the WEC predictions are from 2010, before the Fukushima Daiichi accident, so the predictions of nuclear development is more optimistic. In the IEA scenario fossil fuels continue to dominate the generation fuel mix, from 67% in 2010 to 57% in 2035. Still coal remains the single biggest fuel source, even if its share is declining. The shares of natural gas and renewables other than hydro will increase. All together this means than the CO_2 emission per TWh will decline. The share of coal in the OECD countries will decrease from about 34% in 2010 to 21% in 2035, while the shares in the non-OECD countries will decline from 47% to 39%. Around 18% of the gross additions of thermal (fossil-fuelled and nuclear) capacity projected through 2035, or about 520 gigawatts (GW), are already under construction (IEA, 2012). A lot of plants also have to retire and in the period 2010–2035 around 2,000 GW will be shut down and replaced with more modern technology. Most of the retiring plants are in OECD countries, where the average age of plants is significantly greater.

Still coal remains the single biggest fuel source in 2035

The developments will be quite different at different continents. The largest growth rate will most likely be seen in Africa. There will probably be a severe competition between the water required to produce the necessary amounts of energy and the water needed for food production and sanitation. Similar problems are evolving in the Middle East, China, and India. All of them already suffer either from water stress or water scarcity, or will do so soon.

There has been a lot of uncertainty surrounding nuclear policies after the Fukushima Daiichi accident in 2011. Several countries have altered their policies in the face of public concerns about the safety of nuclear reactors. These changes have been taken into consideration by IEA in their New Policies Scenario. This includes the retiring plants in Germany and also a temporary delay in issuing approvals for new plants in China. The International Atomic Energy Agency (IAEA) reports that at the end of 2013 there were 72 nuclear reactors under construction in the world, totaling 69 GW of capacity (IAEA, 2014). More than half of these are being built in China (29 reactors, 28.8 GW) and in Russia (10 reactors, 8.4 GW).

Table 9.11 shows that by 2035, renewables (hydro, solar PV and wind) account for almost one-third of total electricity output. Solar grows more rapidly than any other renewable technology.

Renewables will be the second largest source of electrical power generation already in 2015 (about half the coal demand), and by 2035 the renewables will be very close to coal as a source for electrical power.

> *By 2035, renewables (hydro, solar PV and wind) account for almost one-third of total electricity output.*

The total investments in electrical power systems during the 25 year period are expected to be an appalling US\$16.9 trillion (10^{12}). Transmission and distribution systems will require the major part 43%, while investments in wind power will be 13%, hydro 9% and solar PV around 7%.

9.4.2 Water requirements for electrical power generation

The couplings between water use and electric power generation are summarized in Table 9.12.

Table 9.12 Water use for electrical power generation.

	Connection to water quantity	Connection to water quality
Thermoelectric (fossil, biomass, nuclear)	Surface water and groundwater for cooling and scrubbing	Thermal and air emissions impact surface waters and ecology
Hydroelectric	Reservoirs lose large quantities to evaporation	Can impact water temperatures, quality, ecology
Solar PV and wind	None during operation; minimal water use for panel and blade washing	None during operation; minimal water use for panel and blade washing

Source: DOE (2006), Table II-1.

The bulk of water requirements for energy production is due to cooling at thermal power plants. Thermoelectric power plants, independent of fuel type, need cooling and process water. The amount of water depends on the cooling system used. The water used is either wasted or recovered and returned to its source.

Large volumes of water have to be withdrawn for the cooling, as described in Table 9.6. Most of the water used for cooling in thermal power plants is returned, but typically some 3% is consumed, mostly due to evaporation. As a comparison, the water use for agriculture is different, as exemplified by the USA. Of the irrigation water 60% is consumed by evaporation and transpiration while another 19% is lost in conveyance. The latter may be available as a source for other uses.

On a global scale there is still no established method to measure the net evaporation from hydropower dams. The evaporation rates can vary considerably from region to region (more discussion in Chapter 10.2). The water usage for hydropower will be further discussed in Chapter 10.

Water is required to produce biofuels, mostly for irrigation of biofuels feedstock crops. Water use for biofuels production varies considerably because of differences in irrigation needs among regions and crops. Biofuel water requirements are described in Chapter 12.

9.4.3 Predictions of water requirements for electrical power

The water use for cooling in thermal plants will decrease as the plant efficiency increases. In the IEA scenario for the next 25 years it is expected that the average thermal efficiency of coal-fired plants will increase from 39% in 2010 to 42% in 2035. Old plants using subcritical technology (see Chapter 13) will be retired and more advanced plants are built. By 2035, almost 20% of all plants in operation are advanced, compared with only a few percentage points today. There is a small decrease in electricity generation.

As noted in the introduction of this chapter the withdrawals for power generation in 2010 were some 540×10^9 m^3 (bcm). There will be a small increase of the total withdrawals to 560 bcm in 2035. There are two trends that will cause changes in different directions. One trend is the reduction of generation in subcritical coal plants that use once-through cooling, particularly in the US, China and EU. This will reduce global withdrawals by coal-fired plants by almost 10%. Then there will be a growth in generation from newly built nuclear power plants that use once-through cooling that expands water withdrawals for nuclear generators by around 35%. The other trends is that once-through cooling will be replaced by wet tower cooling, which will reduce the withdrawals but increase the consumption of water. Consumption of water in the world's power sector is expected to increase by almost 40% in the IEA New Policies Scenario. Another way to illustrate the water need is by the water intensity, which is defined as the water withdrawal or consumption per unit of energy produced. The withdrawal intensity of global energy will decrease by 23% until 2035 while the consumption intensity will increase by 18%.

An increasing share of gas-fired and renewable generation will play a significant role in reducing additional water use in many regions. As noted in Table 9.11 global electricity generation will grow some 70% over 2010–2035, while the water consumption for electricity generation will increase even more, Table 9.13.

Table 9.13 Prediction of the water-for-electricity consumption (in billion m^3) according to the World Energy Council (WEC, 2010a).

Year	World total	Coal	Oil	Gas	Nuclear	Hydro	Biomass
2005	41	13	1.3	2.5	7.6	16.5	0.4
2020	56	17	1.1	4.9	9.3	22.3	1.2
2035	74	22	1.1	6.5	14.8	26.8	2.6
% increase 2005–2035	80	69	–15	260	95	62	650

The values for the fossil fuels are for electric power only. The values for hydropower water consumption are based on median evaporation rates calculated by Gleick (1994).

The global biofuels supply is expected to increase significantly and consequently the water withdrawals will increase steeply. Due to government policies that mandate the use of biofuels the New Policies Scenario predicts a significant increase of water withdrawals, from 25 bcm in 2010 to 110 bcm in 2035 (340%), and a consumption increase from 12 bcm to almost 50 bcm (>300%) (adapted from Figure 17.7 in IEA, 2012). Note that these values are far higher than the prediction shown in Table 9.9.

The higher water requirements for biofuels production stem from the irrigation needs for feedstock crops for ethanol and biodiesel – primarily sugarcane, corn and soybean – in major producing regions, such as Brazil, the US and China. After 2020 advanced biofuels from waste crops that do not depend on irrigation will be introduced in a larger scale. This should dampen the increase of water use for biofuels.

Water scarcity will almost certainly have a considerable influence on the energy planning. The largest users of water for energy production are the largest electrical power producers, the US, China and India. They need to have significant generating capacity inland, far from the coast. The operations depend on the freshwater availability. Countries like Japan, Korea and Australia can meet most of their electrical power demand from plants located near the coast, where seawater can be used for cooling. Cooling of thermal plants is examined further in Chapter 13.

9.5 WATER CONSTRAINTS FOR ENERGY PRODUCTION

There is no doubt that water may be a serious constraint for a significant increase of energy generation in many regions of the world. In the scenarios presented both by IEA and the World Energy Council it is mostly assumed that the energy constrains can be overcome. This is not always apparent and the water availability may be the limiting factor in many cases of energy system expansion. Not only water quantity but also water quality is affected by energy operations. Consequently water and energy policies need to be integrated.

It is important that governments, in setting policies to make water available for food, ensure that water is also available for energy production and conversion. It is important to remember that without energy to supply the amounts of water needed for all uses there can be no production of food or modern food processing. As energy resources are stretched, more and more unconventional sources become attractive, and many of these (e.g. oil sands, oil shale, and deep gas shale) require large amounts of water, further stressing current and projected systems.

We have already illustrated how technology developments will overcome some of the water constraints, such as more efficient coal-fired thermal power plants. Once-through cooling can be shifted to wet tower cooling and the water cooling systems can be replaced by dry cooling. Solar PV and wind power will not require any water during operation.

The energy sector also has to look for alternative water sources like saline water, treated wastewater, storm water and reused water from oil and gas operations. Water economy has to be developed where the price of water will better reflect its true value (Chapter 8).

A recent study of the crucial couplings between water and energy and water for energy has concentrated on the situation in South and South East Asia (IGES, 2013). These regions are very vulnerable with regard to water availability in the long run. The studies are concentrated on two different geographical locations, one in India and the other in Thailand, to demonstrate the impacts of water scarcity on long-term energy supplies up until 2050. India has enormous requirements for more energy, but has limited water resources. Thailand, on the other hand, has abundant water supplies. The study, not surprisingly, concludes the urgency to act for water and energy conservation as well as an integrated planning where both of these resources can be considered together. Agricultural issues have to be considered along with water and energy, so that water, food, energy and climate are assessed together.

Coal-based electricity generation is likely to be the predominant electricity supply mix in the foreseeable future in Asia. This kind of generation demands large amounts of water and will put immense pressure on the freshwater resource stocks. Water constraints pose a severe threat to the rate of development in Asia. The very high projected water use in the electricity sector implies that there is a critical trade-off among various water uses, particularly in water stressed hot spots of economic development such as India and China. It is projected that in 2050 electricity generation will account for 20% of the total water demand in India unless appropriate measures are taken to deal with the water scarcity issues from both technical and policy perspectives. The electricity planning of India has been seriously ignoring the issue of water availability (IGES, 2013). More than 60% of the capacity of installed thermal plants were set up in regions where electricity demands are expected to remain very high and, ironically, all these areas are either 'water scarce' or 'water stressed'. Also in water rich Thailand water scarcity is not unknown. The 1200 MW Rayong plant – operated by the power company EGCO – nearly ran out of cooling water in the dry season of 2005. Reduced rainfall caused reduction of hydropower generation in Thailand in 2004.

9.5.1 Some constraints

There are several operations where the water availability becomes a true constraint for energy production or generation. Some examples are:

- The cooling capacity for a thermal power plant can be reduced and threaten the power generation if a river flow or a reservoir level drops near or below water intake structures.
- A hydropower plant capacity will be reduced if the water level of the dam decreases. Any hydropower generation is vulnerable to fluctuations in water availability.
- In many oil and gas reservoirs water flooding is required to support the production. This will keep up the pressure. If the water availability is not secured then the production capacity will suffer.
- Increasing water temperature in rivers, lakes or sea will threaten the cooling of thermal power plants. During recent summers, cooling water restrictions forced several nuclear and thermal plants to reduce production.
- The supply of renewable energy sources is also vulnerable to an increase in extreme weather events. Changes in wind patterns or insolation will affect the variability of wind- and solar-based electricity generation.

It is obvious that regions with water scarcity face many risks in energy generation. Other regions can face risks related to heat waves, droughts, seasonal variations, and climate change. Plants with once-through cooling are particularly vulnerable to water scarcity, since they require large flows of water for the cooling.

Some recent events are mentioned to illustrate the vulnerability (IEA, 2012, Table 17.3):

- *India (2012)*: a delayed monsoon raised electricity demand (for pumping groundwater for irrigation) and reduced hydro generation, contributing to blackouts lasting two days and affecting over 600 million people.

- *China (2011)*: Drought limited hydro generation along the Yangtze River. This caused higher coal demand (and prices) and forced some provinces to implement electricity rationing.
- *Vietnam and the Philippines (2010)*: the El Niño weather phenomenon caused a drought that lasted several months, reducing hydro generation and causing electricity shortages.
- *Southeast US (2007)*: a serious drought forced the Tennessee Valley Authority to curb hydro generation to conserve water. The production from nuclear and fossil fuel-based plants had to be reduced.
- *Midwest US (2006)*: a heat wave forced nuclear plants to reduce their output because of too high water temperature in the Mississippi River.
- *France (2003)*: the serious heat wave during the summer forced EdF (Electricité de France) to reduce nuclear power output equivalent to the production of 4–5 reactors.

9.5.2 Reducing the freshwater need

There are several ways of reducing the freshwater need for energy generation. To reduce the water need for cooling of thermal power plants and fossil fuel extraction Williams – Simmons (2013) has recommended the four Rs: replacement, reuse, recycling and regional responsibility:

- *Replacement*: the use of non-freshwater sources such as seawater, brackish water, produced water and wastewater in place of fresh water.
- *Reuse*: using the same water multiple times in an industrial process.
- *Recycling*: treating wastewater to make it a usable replacement for fresh water in another application.
- *Regional responsibility*: adapting practices to suit the local availability and demands on renewable fresh water.

9.6 CHAPTER SUMMARY

The energy demand for the world will increase substantially during the next decades:

- Fossil fuels will still dominate the energy market;
- Non-conventional oils will require even more water for the extraction;
- There is a disturbing difference in electric energy use between the ‘haves’ and ‘have-nots’.

A renewable energy production should aim at:

- Supporting sustainable development, particularly in the developing world;
- Reducing the environmental impact of energy production and consumption;
- Enhancing energy security.

It is obvious that it is not easy to move the gigantic energy locomotive. Hard work, ideas and regulations are required. John F. Kennedy once told: ‘The great French Marshall Lyautey once asked his gardener to plant a tree. The gardener objected that the tree was slow growing and would not reach maturity for 100 years. The Marshall replied, “In that case, there is no time to lose; plant it this afternoon!”

9.7 MORE TO READ

In the last two years some excellent documents on water footprint for energy have been published. The United Nations World Water Development Report 2014 (UN WWDR, 2014) presents an overview of the water-energy nexus and specifically addresses the water demand in energy in its Chapter 3. The World Bank report on Thirsty Energy (World Bank, 2013) is also recommended. Williams-Simmons (2013), sponsored by BP, gives an easy-to-read and instructive introduction in the topic of water for energy.

The topic of water and energy is a topic for a wide spectrum of engineers. IEEE (The Institute of Electrical and Electronic Engineers) has focused several articles on the water-energy nexus. Some key papers are found in IEEE Spectrum (http://spectrum.ieee.org/static/special-report-water-vs-energy) where the message is plain-spoken: without water, we'd have practically no energy. There are survey papers on shale gas and water, hydropower, carbon capture and biofuel, to mention a few.

10

Hydropower

> *The water falls but the waterfall does not fall.*
> Galton, A. and Mizoguchi, R. (2009).
> J. of Applied Ontology, 4(2), 71–107.

I have to admit that I have admired large hydropower dams. The marvellous engineering work to build these huge structures in order to provide electrical power for us made a great impression on me. In my country, Sweden, some 45% of our electrical power is produced by the hydropower systems in the north of Sweden and then transmitted via huge power transmission lines to the main consumers in the south. I still remember when my father in the 1950s showed me the power line coming from the Harsprånget plant (Map 10.1) in the far North providing power for us more than 1000 km further south. At that time the power line was the world's longest power line with 380 (now 400) kV voltage. Still Harsprånget is the largest hydropower plant in Sweden, providing 977 MW.

Map 10.1 The Harsprånget Hydropower plant, Sweden.

Hydropower is considered a very attractive form of electrical power generation. There are several reasons for this. From a power grid operation point of view hydropower is an excellent source of energy. The electrical power output from a hydropower plant can be changed within fractions of a minute and this makes hydropower the preferred source for frequency control, whenever it is available. When wind turbines or solar panels are injecting energy into a grid, hydropower units can reduce their own output and store extra water in their reservoirs. This storage can then be used to increase hydropower output and fill the gap when the wind drops or the sun is covered by clouds and input from these sources falls.

Like all kinds of energy generation hydropower has its price for the environment, people, and water resources. The water and environmental consequences for fossil fuels, for energy from biomass and for thermal power plants will be discussed in subsequent chapters. Hydropower has other kinds of consequences that should be evaluated in a cost/benefit analysis compared to the environmental impact made by fossil fuel or nuclear thermal power plants or biofuels. It should be emphasized that hydro dams can be used for other purposes than electrical power generation: for flood control, for irrigation and for water storage in dry areas, suffering from long periods without any rain. The impact associated with dams in a cold climate is significantly different from that of dams built in arid or tropical areas.

The global picture of hydropower is described in 10.1. Various consequences of hydropower plants and of dams will be described. A combination of key performance indicators will indicate if hydropower also is a sustainable form of electrical energy generation. The incentives for hydropower are summarized in 10.2. The various economic, social and environmental consequences of dam building are described in 10.3. Some of the conflicts that are a result of dam building are exemplified in 10.4. Small hydropower plants offer great opportunities in many places, as discussed in 10.5. As in most water and energy related issues, an integrated planning is required, Section 10.6. The chapter is summarized in 10.7.

10.1 HYDROPOWER IN THE WORLD

The usage of hydropower varies greatly from country to country. In 24 countries more than 90% of their electricity is generated through hydropower, whereas others generate none at all.

Hydropower generates about 1/6 of the world's electrical energy.

Hydropower is defined as renewable electrical energy since it harnesses the power of water by running through the turbines and discharging it downstream. Hydropower generates about 16% of the world's electrical energy. The top world producers of hydroelectricity are shown in Figure 10.1, with the world total being 3,566 TWh in 2011, growing 7.6% in the two year period 2009–2011 (IEA, 2013b). Significant new development is taking place in China and other regions in Asia, Latin America and Africa. Europe and North America have highly developed markets, with modernization, uprating and conversion at existing hydropower facilities, alongside a smaller number of new projects.

In 2011 the total hydropower capacity installed in the world summed up to 1067 GW (IEA, 2013b). China with 194 GW and the US with 101 GW are the world's leading hydropower producers. As Figure 10.2 shows hydropower is the major electrical energy source in some countries. The generating capacity of the largest dams in the world is depicted in Figure 10.3, with the Three Gorges Dam in the Yangtze River as the obvious number one.

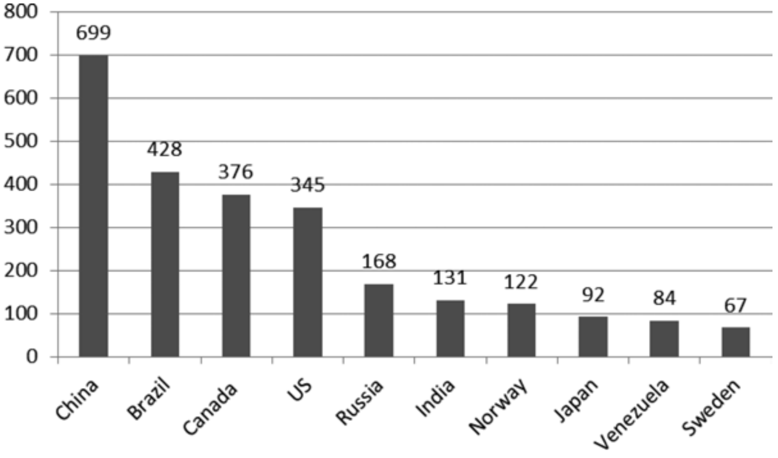


Figure 10.1 The top producers of hydroelectric power in 2011 (TWh). (*Source*: IEA (2013b)).

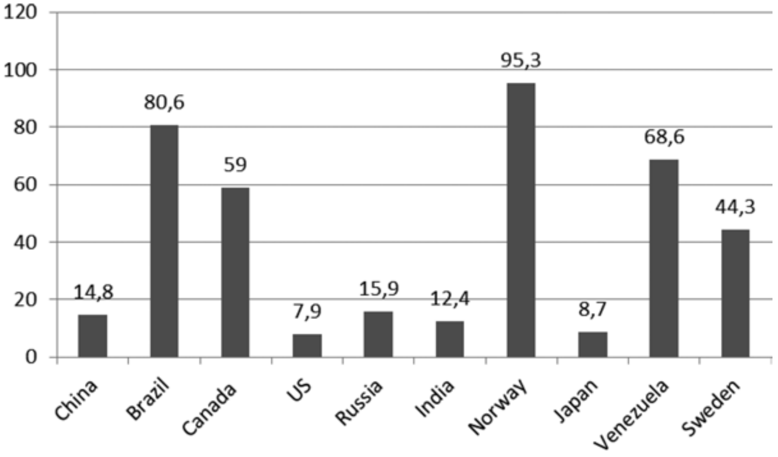


Figure 10.2 The top ten producers of hydroelectric power in 2011 and the percentage of hydro in the total domestic electric power generation. (*Source*: IEA (2013b)).

Knowing the total hydropower energy of 3,566 TWh from the capacity of 1067 GW we find that the hydropower stations are operating, at a world average, only 3350 hours per year, or 38% of the time (compare Table 22.2 and Kumar *et al.* 2011, p 446, where the global average capacity factor for hydropower is shown to be 44%). It should be of interest to compare this with wind power. In Denmark, a pioneering country in windpower, the power plants were running initially some 20–25% of the time. The off-shore 160 MWe wind power park Horns Rev is operating some 3300 hours per hear, or 38% of the time. The typical operating range for off-shore is now 3,500–4,000 hours per year or 40–46%.

The world average of hydropower stations are operating only 40% of the time. This is very close to the utilization rate of wind power.

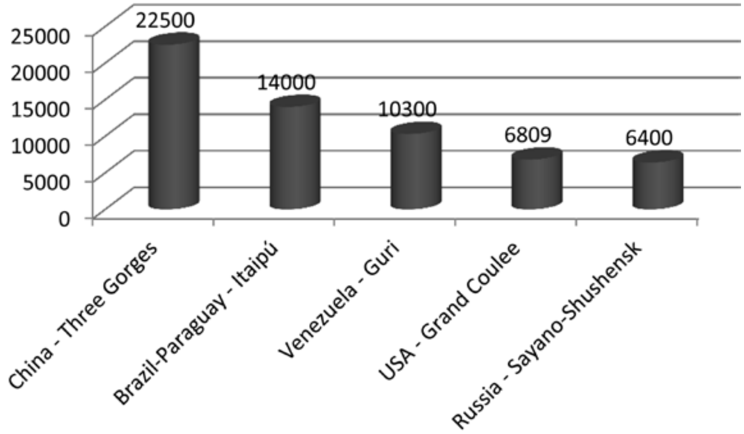


Figure 10.3 The generating capacity (MW) of some of the world's largest hydropower plants. (*Source*: World Almanac (2011) and Wikipedia).

As noted in Table 9.11 the use of hydropower is expected to increase from about 3000 TWh today to about 5600 TWh in 2035 (IEA, 2012). The global capacity is expected to increase from 1067 GW in 2011 to almost 1700 GW in 2035. Nearly 90% of the expected growth will take place in non-OECD countries. In the OECD countries the best hydropower resources have already been exploited, so the potential hydropower growth is limited. The highest hydropower growth will take place in China, India and Brazil (IEA, 2012). China passed a Renewable Energy Law in 2005. The 12th Five-Year Plan, covering the period 2011–2015, calls for 120 GW of additional hydropower capacity by 2015. These plants have maximum energy generation of more than 1000 TWh. China's capacity is expected to almost double between 2011 and 2035, up to 420 GW. As a comparison, the entire OECD is expected to increase from about 450 GW in 2011 to 525 GW in 2035.

In India the expansion of large hydropower, provided for in the country's five-year plan, is uncertain due in part to re-settlement issues. Still the capacity is expected to increase from 42 GW in 2011 to 115 GW in 2035. Huge plans are presented for the extraction of hydropower on the Himalayan slopes. Brazil has a ten-year plan for energy expansion through 2020, aiming for renewables to account almost 80% of total installed capacity in 2020. The main contributor will be hydropower, but also wind power and biomass will be important energy sources. The hydropower capacity is expected to increase from 89 GW in 2011 to 130 GW in 2035 (IEA, 2012).

Africa's energy needs are huge; 590 million of its people still lack access to electricity. Hydropower in Africa generated 105 TWh, or 16% of the electricity, in 2010. The hydropower capacity was 27 GW. Only a small fraction of Africa's hydropower potential has been developed (UNEP, 2010) and the technical potential has been estimated to exceed 1,800 TWh. Most of the hydropower capacity is located in the Republic of Congo, Ethiopia and Cameroon (WEC, 2010b). In the IEA New Policies Scenario, hydropower capacity will rise to almost 80 GW by 2035, including several projects currently under construction. Africa's great rivers have an enormous potential, particularly the Zambezi, the Congo and the Nile, and hydropower is seen as the motive force for future development in Africa. Issues of finance and funding are considered the major hindrances to hydro development. The water footprint is more seldom brought up as an obstacle for hydropower development. Africa's largest hydropower facility is currently under construction on the main stem of the Blue Nile River in Ethiopia. The

Grand Ethiopian Renaissance Dam (GERD) is poised to facilitate regional development with a 63 km^3 reservoir (Lake Nasser further downstream in Egypt holds 111 km^3) and 6,000 MW of power generating capacity. The project is scheduled to be fully operational by 2017.

The prediction of future available hydropower is getting increasingly complex, mainly because of the climate change. The increasing volatility will make the future hydropower much more uncertain. In tropical and midlatitude rivers the water sources are already flowing less or drying up. A study performed by the National Center for Atmospheric research in the USA (IEEE, 2010) found 'significant changes' in the stream flow of a third of the world's largest rivers from 1948 to 2004. While the Pacific Ocean received 6% less freshwater and the Indian Ocean 3% less the drainage into the Arctic Ocean rose by about 10%. For example a drought stricken country like Kenya is quickly developing geothermal and wind power to compensate for unreliable hydropower (Mwangi, 2014).

It is difficult to predict the water consumption for hydropower. On a global scale the World Energy Council has predicted the water consumption depicted in Table 10.1.

The values in Table 10.1 are based on median evaporation rates calculated by Gleick (1994). Evaporation will be discussed below and it is demonstrated that there are extremely different evaporation rates at different sites. Therefore any average may be misleading.

Table 10.1 Prediction of the water for hydropower energy demand (in billion m^3) according to the World Energy Council (WEC, 2010a).

Year	Consumption of water for hydropower (km^3)
2005	16.5
2020	22.3
2035	26.8

Compare the water demand for other primary sources, Table 9.9.

10.2 INCENTIVES FOR HYDROPOWER AND DAM BUILDING

The rationale to build dams includes:

- hydropower generation;
- flood control;
- water storage for irrigation, drinking and industrial use;
- navigation.

The number of high dams has been increasing at an impressing pace. In 1900 there was no hydropower dam in the world higher than 15 meters. By 1950 there were 5300 dams, and only 2 of them in China. In 1980 the world had 36,500 dams and half of them were built in China. Today there are more than 45,000 dams, in operation worldwide in over 140 countries. They primarily serve to store water for irrigation, drinking, and industrial use or to provide flood protection. About a quarter of the large dams have hydropower as their main use or are used for hydro as part of a multi-purpose structure. The heights vary:

- about 40% of the dams are less than 20 m high;
- about 50% of the dams are between 20–60 m high;
- the rest, some 10% are from 60 m upwards to 300 m or more.

10.2.1 Hydropower generation

Hydropower is an attractive form of electrical energy from an operations point of view. Furthermore, a reservoir provides an energy storage that can save the potential energy of the water during long times. This is valuable not only in dry climates but also in cold areas, where the melting snow can be stored to be used during several months of the year. It is obvious that the reservoir should be filled to its maximum level in order to provide a maximum power generation.

A hydropower dam stores energy.

10.2.2 Flood control

Flood control is often a main incentive for a dam construction. The operation for flood control has to be different than the operation for hydropower generation. It is intuitively obvious that the dam has to have some extra volume to catch the flood caused by torrential rains or other weather conditions. Therefore there should be some predictive operation to prepare the dam level for possible flooding events.

> Operation of a dam should be predictive to prepare for possible flooding events.

This is of course not a trivial task. The prediction would need to estimate the volume of the extra water coming and when the dam capacity has to be available. The prediction will always include some uncertainty and this uncertainty has a cost.

The electric power capacity at a hydroelectric plant is approximately:

$$P = k\rho hqg$$

where P is the power (W), ρ the density of water (kg/m^3), h the height in m, q the water flow rate (m^3/s), g the acceleration of gravity (9.81 m/s^2) and k a coefficient of efficiency, ranging from 0 to 1. For our discussion it is sufficient to note that the power is proportional to the height h of the water.

> Any lowering of the dam level will directly create a cost of lost power generation.

Therefore the operators may be hard pressed to keep the dam level at a maximum all the time.

Using the spillways to release water from the dam is a loss of income and many operators have waited to the last minute to use the spillways. Then, in many tragic events, this has been too late, and the dam has caused just the flooding that it should have prevented. Since the flood water reaching the dam has a larger potential energy compared to the situation before the dam was built, the water flow from the spillways will often be more sudden and faster than the natural flood. The consequences in many cases have been dramatic.

The challenge of flood control competing with hydropower generation is an advanced control and optimization problem, where the risk of flooding must be weighed against the risk of losing income from electric power. There is also a competition between hydropower generation and irrigation needs, which is another optimization problem.

10.2.3 Water storage

Water storage has several purposes. In cold places like northern Sweden the water storage is for energy storage for hydropower only and no water is needed for irrigation or drinking water purposes. There are plenty of other water sources available. In an arid country the dams tend to be multipurpose, both for hydropower and for water storage. In a mountainous country we may find a lake that can be used as a dam for hydropower.

Flood control and water storage are important reasons for building dams.

10.2.4 Generating equipment

There are three principal ways of improving operating efficiency within existing hydropower projects, which allow for more electricity generation from the same scheme:

- *Improving water management* and allowing plants to operate at their optimal level of efficiency, by adjusting flows to maximize the available 'head' (drop) at each site.
- *Installing equipment* that is designed to have a higher efficiency over a wider range of water flows through the turbine. This is particularly significant for small projects for which the volume of water flow may vary sharply during rainy and dry seasons.
- *Increasing the flow* to the turbines and reducing losses, through minor changes to the hydraulic passages.

The structural elements of a hydropower project, which tend to take up about 70% of the initial investment cost, have a projected life of about 100 years. On the equipment side, some refurbishment can be an attractive option after 30 years. Advances in hydro technology can justify the replacement of key components or even complete generating sets. Typically, generating equipment can be upgraded or replaced with more technologically advanced electro-mechanical equipment two or three times during the life of the project, making more effective use of the same flow of water. A turbine commissioned in the 1970s, for example, might have a peak operating efficiency of 80–85%, whereas a modern turbine would raise this to 90–95%. The long life and extremely low running costs of hydropower systems make even a modest improvement in output financially attractive.

Long-term cyclical changes in precipitation patterns and the effect on flows in rivers and the operation of reservoirs and hydroelectric plants are a major concern to the energy industry. One example is from north-western USA (Washington State Hazard Mitigation Plan, 2004). A major drought in 2001 caused a significant reduction of hydroelectric power. This lead to the loss of thousands of jobs in the energy-intensive aluminium industry. Loss of hydropower also means less control authority of the power grid via the hydropower plant.

10.3 COSTS FOR DAM BUILDING

All energy generation has an environmental cost. This is also true for hydropower. We will discuss some of these cost factors below. They can be defined by:

- evaporation,
- sediment transport,
- increased erosion,

- increased flood risks,
- changing river flow patterns,
- consequences for fishing, agriculture and biodiversity,
- greenhouse gas production,
- dislocation of people,
- human health,
- environmental consequences.

Hydropower may be the answer to meeting increased energy demand without increasing CO_2 emission, but increased use of hydropower may have detrimental effects on water availability and environmental flows. There are both good and bad hydro projects. Here we will describe some bad hydro systems in order to illustrate consequences that can be used as warning examples. However, there are protocols evaluated, Section 10.5 that can guide the planners to develop projects where sustainability is the key indicator.

10.3.1 Evaporation

Hydropower is a major water user. Water is consumed via evaporation from the reservoir created for hydropower facilities. Factors determining the amount consumed – climate, reservoir design and allocations to other uses – are highly site-specific and variable. That is the reason why measurement approaches are not agreed upon. By one estimate, hydropower operations in the US consume 68 l/kWh on average, with a wide range that depends on the facility (Torcellini *et al.* 2003). This suggests that hydropower plants with large dam capacity at some sites can have some of the highest water consumption levels of any capacity type per unit of electricity generated (see further Chapter 13). Run-of-river hydropower plants, however, store little water, leading to evaporation losses that are near zero.

When the water is stored in a basin instead of flowing in the river in a warm country the temperature will rise. It is obvious that this will cause an increased evaporation. Evaporation in warm countries can be significant. For example, Lake Nasser upstream of the Aswan Dam in Egypt loses about 3 m every year due to evaporation (Demeke *et al.* 2013). In a dry year this corresponds to more than half the flow rate of the Nile River. At an average the Nile River loses 15% of its flow due to evaporation in the Lake Nasser. This of course will influence the hydropower generation capacity. The loss of water is also a significant part of the flow that would be meant for irrigation of farms along the river. Due to the climate change the average temperature is rising. For example, in the Western USA the average temperature has risen about 1°C since 1950, nearly twice the global temperature rise during the entire 20th century. This will further increase the evaporation. A typical reservoir in India loses about 1.5 m per year and in dry areas of Australia the loss can be as much as 3 m per year. An extreme example is the Akosombo dam in Ghana, a giant reservoir having an area of 8,500 km^2. It loses more than 2 m per year which corresponds to about half the capacity of the Volta River in an average year.

Evaporation in dams in hot climates is significant.

It is argued that evaporated water is not consumed but re-enters the hydrological cycle as precipitation. However, the precipitation may not compensate for the evaporation where the water was used previously. If we lose control then it should be defined as consumption since the control of that amount of water has been lost due to the evaporation.

Elementary calculus can qualitatively explain that the water loss due to evaporation is larger when the surface/volume ratio of the basin is large. A shallow reservoir is subject to much more evaporation than a deep one. The water consumption can be expressed in terms of evaporated water per generated electrical energy, or liters/kWh.

Mekkonen-Hoekstra (2012) examined 35 selected hydropower plants and their water footprint. Table 10.2 is extracted from this publication and demonstrates a huge difference in water footprint per generated kWh. There are two principal parameters of interest, the evaporation (mm/year) and the area of the reservoir per generated MW. The selected plants have been primarily built for the purpose of hydroelectric generation, although some serve other purposes as well. The water footprint of hydropower is based on the annual evaporation rate and energy generated. The evaporation from the water surface (in mm/day) has been calculated using the Penman-Monteith equation (McJannet *et al.* 2008) that takes the heat storage in the reservoir into consideration and is valid for a variety of water bodies.

The table illustrates that the water footprint (liters/kWh) has a huge variation, from 3000 l/kWh in the Akosombo reservoir in Ghana to only 1 l/kWh in the San Carlos dam in Colombia. A simple comparison between the first five reservoirs in Table 10.2 shows that their rates of evaporation are of the same order of magnitude. The specific basin area per MW is, however, widely varying. Actually, Mekkonen-Hoekstra (2012) show that there is almost a linear relationship between the water footprint of the power plants and the reservoir area expressed in ha/MW. Figure 10.4 illustrates graphically the reservoir area per MW compared with the gross water footprint for the actual electricity production for some of the plants in Table 10.2.

Since the specific water consumption is so site specific any average number may give a false impression of hydropower water consumption. The location of the hydropower is crucial when the water footprint is considered and averaging can obscure local issues. The consumption is anywhere between negligible and much more than 1,000 liters per generated kWh electrical power. One of the first to relate evaporation to energy generation was Gleick (1993a). He studied reservoirs in California and noted the annual evaporation from an open surface to around 1000 mm/year. The evaporative losses in his study of hydro reservoirs in California ranged from 0.04 to 210 liters/kWh/year. Demeke *et al.* (2013) estimated the evaporation from 13 reservoirs around the world with (gross) evaporation losses ranging from 2 to 6000 liters/kWh. The evaporation has actually been measured in some of the reservoirs, where the Lake Nasser in Egypt is the worst example with more than 6000 liters/kWh of gross evaporation. Also Akosombo in Ghana is measured and found to be 2700 liters/kWh. It should be noted that both Akosombo and Lake Nasser are multipurpose reservoirs. Demeke *et al.* (2013) found reasonable agreements between estimated and measured evaporations for several reservoirs.

Hydropower consumes water, in some cases huge amounts of water.

Table 10.2 Evaporation from some selected hydropower plants.

Hydropower plant	Reservoir area km²	Installed capacity MW	MW/km²	ha/MW	Evaporation mm/year	Estimated water footprint liters/kWh	
						at max energy production	at actual energy production
Akosombo, Volta River, Ghana	8502	1180	0.14	720	2185	1800	3000
Sobradinho, São Francisco River, Brazil	4214	1050	0.25	400	2841	1300	1440
Kariba, Zambesi River, Zambia-Zimbabwe	5100	1320	0.26	386	2860	1260	2300
Nam Ngum, Nam Ngum River[a], Laos	370	150	0.41	247	2411	680	900
Cabora Bassa, Zambesi River, Mozambique	2660	2075	0.78	128	3059	450	670
Yacyreta, Paraná River, Argentina/Paraguay	1720	2700	1.57	64	1907	170	290
El Chocon, Limay River Argentina	816	1200	1.47	68	2089	160	470
Robert-Bourossa, La Grande River[b], Canada	2815	7722	2.7	36	586	24	30
Itaipu, Paraná River, Brazil-Paraguay	1350	14000	10.4	9.6	1808	20	27
Sayano Shushenskaya, Yenisei River, Russia	621	6400	10.3	9.7	486	5.4	13
San Carlos, Guatape River, Colombia	3	1145	380	0.26	1726	0.4	1.1

[a] Major tributary to Mekong River

[b] Part of Hydro-Québec's James Bay Project

Source: Table 1 in Mekkonen-Hoekstra (2012).

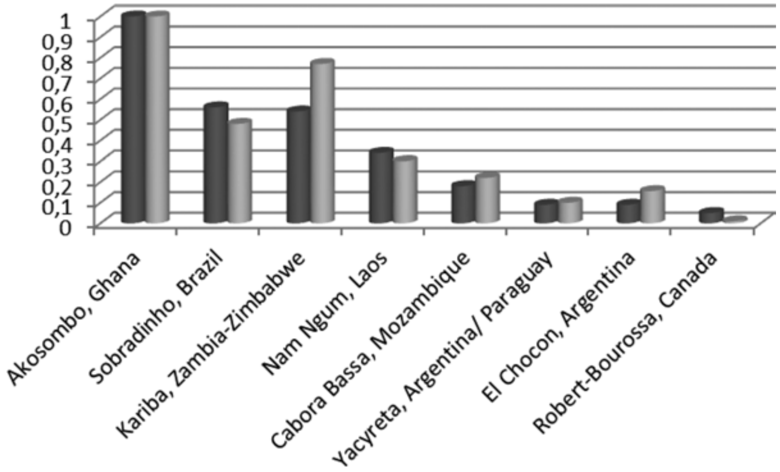


Figure 10.4 Comparison between the normalized values (1 for Akosombo) for the reservoir area per MW (left cylinders) and the water footprint in liters/kWh (right cylinder) for the actual energy generation. Data from Mekkonen-Hoekstra (2012).

10.3.2 Gross or net evaporation?

The calculations of evaporation in the previous section are all *total* consumption due to evaporation. A reservoir's *net* consumption is defined at the added evaporation in a system where natural evapotranspiration occurred before the dam was built. Before the reservoir was created there was evaporation from the area as well, probably not so much from the original flowing river (since in most cases the reservoir area is much larger than the original river water area) but possibly significant from the inundated land. One argument to use the gross evaporation as an indicator is that the water footprint is defined as the volume of water consumption that can be associated with a specific human purpose (Hoekstra *et al.* 2011). With that definition the gross evaporation is motivated as a measure. Under all circumstances it is considered crucial to consider the consumptive use of water in the planning for new hydroelectric plants.

The consequence of the water consumption has to be related to the water availability. Three kinds of water footprints for hydropower have been defined in case studies in New Zealand (Herath *et al.* 2011):

- *Gross consumption (WF_1)* – the evaporative water loss (E_0) from the surface of the reservoir (typically m^3/year) divided by the energy (P) produced by that power plant in the same period: $WF_1 = E_0/P$. This measure is used in Table 10.2.
- *Net consumption (WF_2)* – considers the consequences of the changing land use created by the dam. Some vegetation is replaced by the free-water dam surface. The evapotranspiration (ET) is now replaced by the evaporation (E_0) from the reservoir: $WF_2 = (E_0 - ET)/P$;
- Water consumption taking rainfall into consideration (WF_3, net water balance). If the precipitation is taken into consideration then the total rainfall (RF) during a year can be subtracted from the evaporation during the same period in order to obtain the net loss of

the reservoir: $WF_3 = (E_0 - RF)/P$. This definition of a WF can result in a negative number, which means that the evaporation loss is fully replaced and the rain actually adds water to the reservoir.

One method to calculate the net evaporation for the Eastmain-1 reservoir, owned by Hydro-Québec in Canada is described by Tremblay *et al.* (2014). More than 25,000 measurements were recorded over five years. A critical review of the various ways of calculating evaporation has been made by Bakken *et al.* (2013). The authors find that using the gross evaporation as a measure of the water footprint for hydropower generation is sometimes oversimplifying the issue. In the cases where both the gross and the net water consumption estimates are calculated, the net values are in the range of 12–60% of the gross water consumption. The authors also emphasize that an adequate methodology for calculating water consumption in reservoirs based on natural lakes is needed. Here the evaporation losses should not only be related to the hydropower production. Also Demeke *et al.* (2013) found that the net evaporation reduces the footprint value considerably, compared to the gross evaporation. However, the calculations are more complex, given the difficulty to evaluate the natural evaporation.

10.3.3 Multipurpose dams

Many hydroelectric dams are designed to serve other purposes on top of hydropower generation. In the situation where a dam is being used for other purposes, then the water consumed through evaporation or evapotranspiration should be split between the different users. The potential risk of impacts generated by this consumption should also be shared. However, it is important to emphasize that hydroelectric generation is generally a large water consumer. Therefore, in allocating water to hydroelectric generation it is advisable to explore the water impact also for alternative uses upstream or downstream of the location of a planned hydropower reservoir.

Evaporation may be significant in arid areas but the dam may still be motivated, since the reservoir will provide water that would otherwise not be available. This argument has to be tested carefully, since the flow pattern of the river downstream is usually affected.

10.3.4 Sediment transport

All dams collect silt and this determines the life span of the dam, depending on the silt level of the river. Dams in rocky areas will last longer since the river will carry only little silt. The silt that accumulates in the dam will of course sooner or later fill up the dam. The dam is simply a giant sedimentation basin.

Several examples can be mentioned where hydro dams have collected huge amounts of silt. The Tavera dam in the Dominican Republic was commissioned in 1973. In eleven years it had collected silt to a depth of 18 m. Colorado River in the USA used to transport huge amounts of silt before Hoover Dam and Glen Canyon were built. The pioneer explorers joked that the river was ‘too thick to drink and too thin to plow.’ Now enormous volumes of silt are trapped in Lake Powell and Lake Mead along the River (Powell, 2010). Consequences of silt transport are also described in Chapter 10.3 concerning the Yellow River (see Map 10.4) and the Nile River. Another example of this problem is along the mouth of the Volta River in Ghana. Akosombo Dam has cut off the supply of sediment to the Volta Estuary, affecting also neighboring Togo and Benin, whose coasts are now being eaten away at a rate of 10–15 m/year. A project to strengthen the Togo coast has cost US$3.5 million for each km protected. The story is the same on coastline after coastline where dams have stopped a river's sediments (Pottinger, 1996).

It is estimated that 0.5–1% of global water storage volume is lost annually as a result of sedimentation (Palmieri *et al.* 2003). This would correspond to a loss in storage of some 45 km^3 per year. The authors assume that if the average reservoir volume is 150 million m^3, then 300 large dams have to be built annually just to maintain current total worldwide storage. This would require US$13 billion per year to replace this storage, even without taking into account the environmental and social costs associated with new dams. Earlier, a mid-1980s study for the World Bank found that world reservoirs contained more than 1000 km^3 of sediment, almost 1/5 of worldwide storage capacity. As Figure 10.5 shows the amount of lost volumes are quite different in different parts of the world.

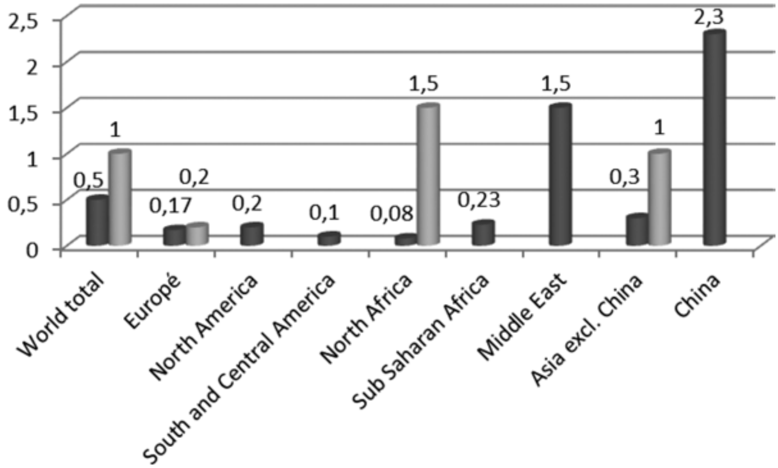


Figure 10.5 Annual loss due to sedimentation (in % of residual storage) in different parts of the world. For regions with two bars the left one is the estimated minimum and the right one the maximum. (*Source:* Palmieri et al. (2003), Table 1)).

Mostly it is not economically feasible or technically possible to dredge the silt. Also, the silt has to be stored somewhere. With a lot of silt in the river the life span of the dam will be reduced to become much shorter than many economic considerations at the design phase.

The trap of the silt in the dam will have serious consequences downstream. Before the dam the silt was mostly a valuable fertilizer to the fields downstream. Now the farmers have to replace the silt with chemical fertilizers. It requires a lot of energy (that may be required from the hydropower plant at the dam) to manufacture them (see Chapter 6.3) and the farmers have to pay a relatively high price for the fertilizers. Furthermore, eutrophication in dams is another serious problem.

Hydro dams often become huge sedimentation basins for silt.

The silt free water downstream of the dam will flow faster. The water flow will scour the river basin to become deeper. This is a recognized problem in the Nile, in the Rhine as well as in the Missouri-Mississippi rivers. This in turn makes flooding more probable.

Then there is the problem of the destruction of deltas due to the silt free waters. Well known examples are the Nile River delta and the Mississippi River delta. The delta lands are simply washed away and this will often cause salt water intrusion.

10.3.5 Increased erosion

There is an increased risk for erosion in some areas, exemplified here by the situation in China. The erosion depends on the soil characteristics, on the slope of the land at the dam and many other factors. Jiao Yong, the vice minister of water resources, has noted that more than 46,000 reservoirs must be rebuilt to ensure that surrounding farmlands and communities are safe from flooding and have enough water for irrigation (Water 21 Global News Digest, 18 October, 2011). Funding will also be needed to protect the massive Three Gorges dam from geological disasters and pollution (see further Chapter 10.4).

10.3.6 Increased flood risks

The operation of a dam to avoid flooding is both difficult and risky. The risks for downstream flooding have to be weighed against the risk of lost income from the hydropower, and this puts a lot of pressure on the operating personnel. If the spillways are opened too late from an overfilled dam then the risks for flooding are much greater and more sudden than would have happened during the natural river flooding.

There are several terrifying examples of flooding:

- *The Hirakud Dam, River Mahanadi, India*: the Mahanadi, rising in the state of Madhya Pradesh, is an important river in the state of Orissa (eastern part of India). In the upper drainage basin of the Mahanadi periodic droughts contrast with the situation in the delta region where floods may damage the crops in what is known as the rice bowl of Orissa. Hirakud Dam was constructed to help alleviating these adverse effects. With its 26 km the dam is one of the longest dams in the world. The construction was started in 1946. Unfortunately the operators have kept the dam too full, which prevents adequate flood control. After the dam completion the frequency of serious floods in the river's delta has more than doubled. During the last ten years two serious accidents have happened with 80 people drowned in the first case and more than 60 in the second one (Kumar *et al.* 2012).
- *China*: China Daily has reported that 322 dams have failed during the last 50 years. The worst disaster occurred in 1975 in the Henan province (Map 3.1). The 120 m high Banqiao dam in the River Ru gave away after a typhoon had hit the area. It is estimated that between 80,000 and 200,000 people were killed. The year 1975 was one of the wettest years on record in China. Chinese government reports have indicated that about 250,000 were killed as a result of dam collapses, and more than 11 million people were left homeless.
- *Kainji dam, Niger River, Nigeria (*Map 10.2): a big flood in 1999 caused a panic operation of the dam and the spillways were opened too quickly. 60 people died and some 80,000 people got homeless. In 2001 more than 100 people died in northern Nigeria after water had been released from two dams. In 2003 another 39 people were killed from a release of water from the Shiroro dam (Pearce, 2006).

Hydro dams – operated incorrectly – may increase the consequences of flooding.

- *La Exparanza dam, Hidalgo, Mexico (*Map 10.3): too quick releases of water from the dam in 1999 caused around 100 deaths. This is still not confirmed in any scientific report.
- *Shadi Kor River, Pakistan*: the 300 m wide dam burst after heavy rains and more than 100 people drowned.
- *India, 2013*: The construction of a dam may cause serious risk for flood damages. In June 2013 a brutal flood, following days of torrential monsoon rains, killed more than 6000 people, leveled riverbank communities, and battered hydroelectric projects across the northern state of Uttarakhand in India's Himalayan region (Schneider, 2014). The flood washed away 25 small hydro projects, and seriously damaged 10 big projects in two narrow river basins, Alaknanda and Bhagirathi. An expert commission concluded that existing hydropower projects aggravated the damage. Mountains of silt, sand, and boulders excavated during the construction of the hydropower plants were left unmanaged along the riverbanks. The rushing high water scoured the banks and pushed the mud and boulders downstream, burying low lying communities. The tragedy will also have long term economic consequences for future hydro projects. Insurance companies have changed their risk perception of hydro power plants and have asked for double or triple the earlier rates for power projects.

Map 10.2 The Niger River basin.

Map 10.3 Mexico.

10.3.7 Changing flow river patterns

Dams will alter the flow and sometimes the temperature of the river water. As remarked, there are two phenomena. Less silt in the water creates a different flow pattern. Increasing temperature in the dam will result in an increasing temperature of the downstream river water.

Filling a dam will have a great impact on the downstream conditions. It is now calculated how to fill the GERD reservoir in Ethiopia. The policies adopted for filling and managing the massive reservoir will directly impact the millions of people in downstream countries who rely on the Blue Nile's waters. King-Block (2014) have addressed the challenge of filling the reservoir. To address this challenge, numerous filling policies have been simulated and evaluated using a climate-sensitivity approach to estimate impacts on reservoir filling time, hydropower production, and downstream flows.

10.3.8 Consequences for fishing and biodiversity

While the expansion of hydropower is expected to double it could reduce the number of our last remaining large free-flowing rivers by about 20% and pose a serious threat to freshwater biodiversity. The hydropower boom occurs primarily in emerging economies in South America, Southeast Asia and Africa. These regions also hold some of the world's most important sites for freshwater biodiversity. A new database has been developed and announced in October 2014 to support decision making on sustainable modes of electricity production (www.freshwaterbiodiversity.eu).

There is a massive hydropower development in the Mekong River Basin, which is the site of the biggest inland fishery in the world. Fish migration routes between the river's downstream floodplains and upstream tributaries can be blocked by the hydro dams. It has been estimated (Ziv *et al.* 2011) that the completion of 78 dams on tributaries will have catastrophic impacts on fish productivity and biodiversity.

Consequences for the fishing industry have been reported in several cases (Rosenberg *et al.* 1997). Some examples can be mentioned: after the Aswan Dam in Egypt was built the Nile River Delta's sardine fishery has been significantly affected. The probable cause is the changing saline mix. Dams on the Niger River decreased catches by more than 30%. In the Pacific Northwest in the USA the number of wild salmon returning to the Columbia River is less than 6% of the number before the dams were built. It is documented that the W.A.C. Bennett Dam on the Peace River in north-western Canada has dramatically disturbed the fisheries in the Peace-Slave-Athabasca Delta.

10.3.9 Greenhouse gas production

Greenhouse gas production is usually not associated with hydropower. However, there are some spectacular exceptions that will illustrate the need to consider GHG so that it can be avoided. The Balbina reservoir is located in the Uatumã River some 150 km north of Manaus in the Amazon rainforest, Brazil. The installed electric power capacity is 250 MW while the average delivery is 112 MW. The dam was built in the 1980s to provide pollution-free electrical power to the city of Manaus. The reservoir has a large area (2360 km^2) but an average depth of only 5 m. The flooded rainforest has of course provided a lot of organic material on the bottom of the reservoir. This is now being decomposed anaerobically and produces methane. The greenhouse effect of methane corresponds to about 8 times the carbon footprint of a coal-fired power station with the same capacity. The decomposition will last for a long time since more organic material is transported by the river to the reservoir. This organic material would almost surely be decomposed aerobically in the river without the dam and would not cause the methane footprint (Fearnside, 1989).

There are attempts to calculate the global greenhouse gas footprint caused by methane in reservoirs. It is estimated that reservoirs are causing some 20% of all the man-made methane in the atmosphere. The result is controversial but no more evidence has been reported.

10.3.10 Displacement of people

Reservoirs may cover people's homes, important natural areas, agricultural land, and archaeological sites. So building dams can require relocating people. It is estimated that some 40 to 80 million people have been displaced globally as a result of dam constructions.

Some 40–80 million people have been relocated due to dam constructions.

Ledec- Quintero (2003) reports that the number of people physically displaced by hydroelectric projects ranges from zero to over 50,000 in Latin America and significantly more than 1 million in China. Table 10.3 shows some of these forced resettlements, expressed in relocated people per MW.

Table 10.3 Land area flooded and people displaced in large hydropower projects.

Project	Capacity MW	Reservoir area km²	People displaced	People displaced/MW
Three Gorges, China	18,200	1045	>1,300,000	>70
Itaipu, Brazil/Paraguay	14,000	1350	59,000	4
Yakureta, Argentina/Paraguay	3,100	1650	50,000	19
Cabora Bassa, Mozambique	2,075	2740	250,000	120
Aswan, Egypt	2,100	5250	100,000	48
Sobradinho, Brazil	1,050	4214	65,000	62
Kariba, Zambia/Zimbabwe	1,320	5100	57,000	45
Balbina, Brazil	250	3147	1,000	4
Akosombo, Ghana	1,180	8502	80,000	68

Source: Ledec- Quintero (2003), Table 2; Wikipedia.

The construction of the Three Gorges dam forced more than 1.3 million people to be displaced. Some estimates are 1.5–2 million. Later the Chinese Government has announced that an additional 3–4 million people would have to be relocated due to the pollution and landslide threats.

10.3.11 Water quality

The impact on water quality of hydropower plants is very site specific and depends on the type of plant, the operation and, of course, the water quality before it reaches the plant. One important aspect of water quality in the reservoir is the dissolved oxygen (DO) concentration. In large and deep reservoirs the DO concentration may be lower towards the bottom, where watersheds yield moderate to heavy amounts of organic sediments. If there is a bottom intake the low DO may create problems, both within and downstream from the reservoir, for the aquatic life. This can be mitigated by multi-level water intakes in reservoirs, and by new turbine designs.

Run-of-river plants are often used to improve DO levels and retain floating debris for disposal. Where there is significant waste entering the reservoir from upstream sources, managing the water quality in the reservoir may be very challenging.

10.3.12 Human health

Bilharzia, or schistosomiasis is a water-borne disease, currently infecting more than 200 million people. It is a common problem in tropical areas that after the building of dams and reservoirs both malaria and bilharzia have increased. Another problem, often overlooked, is that the local people over the centuries have developed a flood dependent agriculture with a varied food production. When the positive effects of the flooding are gone, then the food production has in fact decreased with a resulting malnutrition. The reason is often that the food production consists of monocultures grown on irrigated land. See further Abramovitz (1996).

10.3.13 Environmental consequences

This is of course the most noted consequence. The natural beauty of the nature that is flooded by the dam, the lost grandeur of the free flowing river water is worth a great price, but how much? The land that used to be a great touristic attraction is now lost. Sometimes a pretty lake is created but in most cases the value of the hidden nature was higher. The economic value of tourism should not be underestimated.

The electric power generation can be related to the area flooded by the hydropower dam. Table 10.4 gives some comparisons.

Table 10.4 Comparison of generation per area flooded of some hydropower projects.

Hydropower plant	Reservoir area km^2	Installed capacity MW	MW/km^2	ha/MW	Generation (TWh/year)	Generation per area (GWh/year/km^2)
Three Gorges, China	1045	22400	21.4	4.7	80–140	80–140
Itaipú, Brazil/ Paraguay	1350	14000	10.4	9.6	95–105	70–75
Aswan, Egypt	5250	2100	0.4	250	15–23	3–4
Balbina, Brazil	2360	250	0.11	940	0.97	0.4

Source: Wikipedia.

It is quite apparent that a plant with a large reservoir area per generated unit of energy is causing a large environmental cost.

10.4 EXAMPLES OF HYDROPOWER AND WATER RESOURCE CONFLICTS

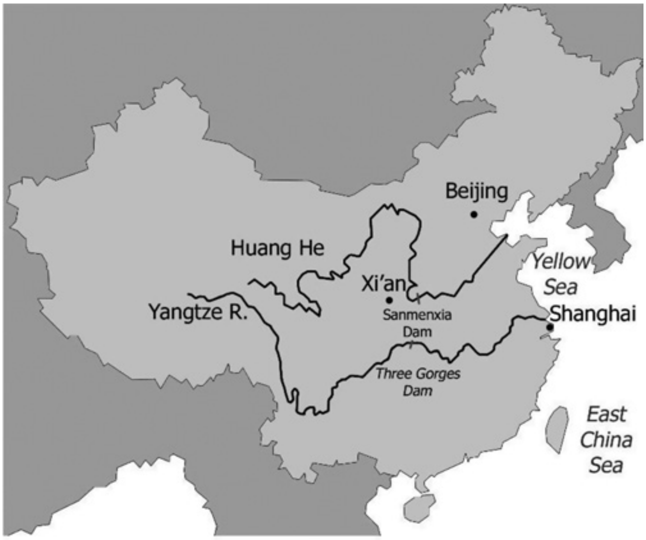
10.4.1 China

China has about 20% of the world population but only 7% of its fresh water. This illustrates the enormous dependence on water resources. During the last 50 years China has built 85,000 dams and around a quarter of them are large. This means more than four dams have been built every day of the year for the last half century. The dams are providing irrigation, flood control, hydropower and storage capacity for the dry seasons. Projects on the Yellow River alone have used enough concrete to build 13 Great Walls. During this period the overall water use has increased a factor of five, while the urban water supplies have grown a hundred times. The nation has budgeted 2 trillion (10^{12}) Yuan (CNY, some 300 billion US$) for hydropower and water infrastructure projects in 2011–2015 (China Daily, 8 November, 2011). The nation has also given top priority to controlling the floods and droughts that have affected millions of people and will spend around 4 trillion Yuan (some 600 billion US$) on water conservation projects over the next ten years, which means that the current spending of 200 billion Yuan per year will be doubled to 400 billion per year. Still, there is a lot of discussion concerning environmental protection and disaster prevention.

China is vulnerable to water scarcity. In 2011 the worst drought to hit central China in half a century brought water levels in some of the country's biggest hydropower producing regions to critical levels (Stanway, 2011). High temperatures and record low rainfall in 2011 caused water levels on the middle and lower reaches of the Yangtze River to dwindle, cutting support to thousands of hydropower plants as well as millions of hectares of farmland. Official figures from Hubei province in May 2011 showed that 1,392 reservoirs in the region were too depleted to generate any electricity at all. China is such a large country that virtually every year some part of it is hit by disastrous droughts or floods, many of them caused by fluctuations in the Yangtze, the country's longest river stretching from Tibet to Shanghai.

10.4.2 The Yellow River, China

The Yellow River (or Huang He as it is known in China) is one of the grand rivers of the world (see Map 10.4). In China it is called the 'joy and sorrow'. The source is in Tibet at an altitude of about 4200 m and around 5500 km downstream it reaches the Bo Hai gulf, some 300 km southeast of Beijing. The name of the Yellow River is inspired by its colossal amount of yellowish silt, considered the world's siltiest river. It has more than three times the sediment discharge of the Mississippi. The silt concentration is about 40 kg/m^3 compared to Mississippi's around 0.5 kg/m^3. This became an expensive lesson when the Sanmenxia Dam at Three Gate gorge was built around 1960 (the message on the Dam says: 'When the Yellow River is at peace, China is at peace'). Thick silt filled the dam to the brim in only two years, causing flooding of the rivers upstream and threatening catastrophic cascade downstream if the rising waters toppled the dam. A decade of hard reconstruction ultimately saved the dam, but the capacity had to be reduced to only 5% of its original planned size. Actually another huge dam had to be built simply to correct for the problems created by Sanmenxia. Of course this limited the hydroelectric capacity as well as the irrigation capacity. As a result of the ongoing accumulation of silt trapped within dams and dikes along the Yellow river, the river bed has rised to an altitude of several meters above the surrounding landscape. The suspended river is rising by about one meter every ten years and dikes have to be built higher and higher to keep it in its bed.



Map 10.4 Huang He (Yellow River) and Yangtze, the two great rivers of China.

Another alarming side effect of the hydraulic engineering of the Yellow River has been that the river is drying up. The proliferation of factories, farms and cities is sucking the river dry. The remaining water is seriously polluted. About 50% of the Yellow River is considered biologically dead. This has been observed since the early 1970s, when the River did not reach the sea at the Bo Hai gulf. The average length of the dry area was about 130 km in the 1970s and grew to the peak of about 700 km in 1995. In 1997 the river failed to reach the sea for 7.5 months. The Chinese government then decided that diversions from the river would be rationed so that some water – a minimum of 50 m^3/s – always flowed to the sea.

Northern China is dry and the water shortage is severe. The serious pollution together with the lack of water can have a devastating impact. The Premier Wen Jiabao stated in 2011 that the shortage of clean water threatens 'the survival of the Chinese nation.'

Part of China's water crisis is related to the climate change. The nation's three famous rivers, the Yellow, the Yangtze and the Mekong, originate in Tibet. The glaciers and vast underground springs of the Qinghai-Tibet plateau – known as China's 'water tower' – supply nearly half of Yellow River's volume. The Chinese weather bureau reports that the climate at the river sources is getting hotter and dryer. Already, more than 3000 of the 4077 lakes in Qinghai Province's Madoi County have disappeared (Map 3.1). The glaciers are shrinking at a rate of 7% per year. Melting ice may add water to the river in the short term, but the long term consequences could be fatal.

10.4.3 Yangtze River and the Three Gorges

There has been a dream of China's leaders for the bigger part of the 20th century to build the Three Gorges dam (Map 10.4). The dam was conceived to control flooding that over the centuries has killed hundreds of thousands of people. Only in the last century floods from the Yangtze – known to most Chinese as Chang Jiang, Long River – has claimed more than 300,000 lives. Yangtze is the world's third longest river – around 6400 km – after the Nile and the Amazon rivers. Its waters irrigate China's 'land of fish and rice', the great central valley where close to half the nation's food is grown. Its watershed encompasses some 1.8 million km^2, a fifth of China's total land area. It irrigates more than a third of China's agricultural output and carries some 75% of China's internal waterborne commerce. It divides the country north and south in matters as fundamental as culinary taste and religious perspective.

The year 1998 was a wet year in the south of China and the Yangtze River reached its highest level since 1954, 15 m above the normal. More than 7 million people along the river in the large city of Wuhan were seriously threatened by the flooding Yangtze. Surprisingly only some 2000 people lost their lives. Millions were left homeless as a result of the flood. The regular Yangtze floods were stated to be a major reason to build the Three Gorges Dam. The Dam should also provide a huge amount of hydropower and at the same time be able to supply water to the dry North.

The Three Gorges (the Qutang Gorge, the Wu Gorge – the Witches Gorge – and the Xiling Gorge) project is certainly the most ambitious project since the Great Wall. The dam has swallowed the canyons of the Yangtze River. The waters behind the Three Gorges Dam, the world's largest hydroelectric project, reached their maximum level of 175 m on 26 October, 2010 (China Daily, 31 October, 2010). The dam began backing up water in 2003. It is only at a level of 175 m that all 26 of the generating units, each with a 700 MW capacity, will be fully operating. The output at 175 m will be 84,7 TWh (this corresponds to only 53% utilization) which is 10 TWh more than what would be generated at a level of 156 m. The dam is more than 1.5 km wide and the reservoir is almost 600 km long (see Table 10.4). The generating capacity, Figure 10.3, is the largest in the world. On 30 October, 2011 the reservoir level hit the 175 m mark for the second time (China Daily, 8 November, 2011). At the same time the water level of the downstream riverbed of the Yangtze River fell to 4.55 m in Nanjing, posing a potential threat to shipping. The reason was dry weather in combination with water being saved for the Three Gorges reservoir (China Daily, 26 October, 2011).

The cargo handling capacity along the Three Gorges has grown eightfold since 2008.

There is a worry about the geological impact of the high water level. The edges of the reservoir are very fragile, according to Yichang Land and Resources Bureau. There has been a succession of landslides, erosion activity and sedimentation in the reservoir area around Hubei's Zigui and Badong. The land in the reservoir area is depositing about 40 million tons of sediment into the reservoir annually.

Chang Jiang is one of the most sediment-filled rivers in the world. The source of the river is in the mountains at an altitude of about 6600 m. After almost 5000 km it flattens out close to Chongqing, upstream of the Three Gorges dam, and despite the flushing power of its current, leaves immense bunkers of vole-grey sand along the city's riverbanks when monsoon floodwaters recede each year. It is estimated that the stillwater reservoir will cause even more sediment to be deposited, obstructing the passage of deep-draft vessels. Before the Dam, rich sediment deposited by the river from the Sichuan Province and the last 1500 km towards the delta close to Shanghai have made the Yangtze Valley China's most fertile region. How the reduced sediment flow will affect the delta is debated.

One of the views expressed by the critics is that sediments will make the deep draft harbour of Chongqing (Map 3.1) – China's largest city with about 30 million inhabitants and nearly the size of Austria – unusable and impede the generation of electric power. Another great problem is all the pollution that is flushed from abandoned factories left to drown. This will cause chemical poisoning of the river.

Freshwater shortages have turned up in Shanghai at the river mouth because the decreased flow in the dammed river was no longer able to offset the force of the tidal inflows from the East China Sea.

The Three Gorges Corporation plans to put 480 million Yuan (around US$ 70 million) into water and land conservation and ecological conservation by 2012 (China Daily, 8 November, 2011).

10.4.4 Tibetan Plateau, India and China

A cascade of dams is planned for the Yarlung Zangbo river (known as the Brahmaputra in India) and its tributaries. Until 2010 the Yarlung Zangbo was one of the world's last undammed rivers. This is one of the world's great trans-boundary rivers – which starts on the Tibetan Plateau before passing through India and Bangladesh. The Yarlung Zangbo runs alongside the Himalayas from west to east along the rift created by the impact of the Eurasian Plate. It cuts through the Tibetan Plateau and then forces its way to form the world's deepest gorge before it makes its way to South Asia where it joins the Ganga and flows to the Indian Ocean.

In the late 20th century, this gorge was recognised as the world's deepest. In the 400 kilometres from the top of the gorge, the river twists around the mountain of Namcha Barwa (known as the Great Bend) and drops more than 2,000 m. It is estimated that a tunnel that cuts the river's natural loop could carry 2,000 m^3/s with a drop in altitude of 2,800 m. This is enough to power 50 GW of hydropower. This could be the largest hydropower project in human history – about three times the size of the Three Gorges Dam. Eleven hydropower stations are planned on the river, three along the middle reaches from Sangri to Gyaca, and nine on the gorge up to the Great Bend, with total generating capacity of 60 GW (Yong, 2014).

The scale of dam building planned by China and India could have disastrous ecological consequences. There are powerful geological stresses, and seismic activity and landslides are common. More than 100 active landslips or mudslides have been found and any future earthquakes could worsen them. In the early 1950s, an earthquake of magnitude 8 on the Richter scale caused many secondary landslides, which resulted in sustained flooding downstream. We still don't know what the long-term impact of climate change will be on the Tibetan Plateau, but the glaciers and snowlines of the Himalayas are retreating, depriving the rivers of a source of water.

The competition for water between China and India will become apparent. China has already begun to construct a 700 MW capacity dam on the Yarlung Zangbo River. There is a fear in India that China intends not only to generate power from the river but also to divert some of its water away from the mainstream (Shankar Jha, 2014). China and India are entering into an undeclared race to capture the hydroelectric potential of the Yarlung Zangbo River basin. India has signaled that it will take up a large number of projects in the Brahmaputra basin. In 2007 the Central Electricity Authority announced plans for 146 projects. The number has now increased to about 200. China intends to build 40 dams on the river and its tributaries. Of these, 20 dams on the Yarlung Zangbo will generate 60 GW of power, while 20 smaller dams upon its tributaries are expected to generate another 5 GW. India plans to generate 22 GW from two large dams on the Yarlung Zangbo and 10 GW from dams on its tributaries. So, together the two countries plan to generate 97 GW of power.

It has to be recognized that rivers are ecosystems and not only water pipes. It is obvious that these ambitious but conflicting plans will heave political consequences. Furthermore the Yarlung Zangbo does not end in India. It flows on to Bangladesh. So, in the same way as India wishes to put demands on China upstream, Bangladesh will demand the upstream India to get its share of the river flow. Bangladesh will certainly press for a multilateral agreement.

10.4.5 The Nile River

The control of the Nile water has been a topic for discussions, conflicts and struggles for millennia. The Nile (see Map 2.6), the longest river on earth, is flowing over 6800 km. It is called the Father of Rivers, the Seed of Civilization. The annual drenching of the Ethiopian highlands that spills over into the Blue Nile and the resulting deposit of silt in the delta that made possible the fecundity of Egyptian civilization. The silt in the water, coming all the way from Ethiopia and Sudan now stops at the Aswan High Dam, 100 m high and 4000 m in length and is stored in the Lake Nasser, the 550-km-long and 13-km-wide lake (Table 10.4) formed by the dam. The construction of the Aswan was observed very closely in Sweden, since Swedish experts were involved in the moving of the Great Temple at Abu Simbel, the Ramses II monument, out of the way of the rising water at Lake Nasser.

The Aswan Dam was officially opened in 1971, being the world's highest rock-filled dam. The dam could store over two times the average annual flow of the Nile and could thus protect Egypt against both extremes of drought and flood. Previously the Nile flooding had damaged a lot of farms, buildings and roads. Its 12 generators (with 2100 MW) produced half of the nation's electrical power when it opened. At the same time the silt coming with the flooding had provided the necessary fertilizers for the farms for millennia. Before the Aswan High Dam, the Nile River carried about 124 million tons of sediment to the sea each year, depositing nearly 10 million tons on the floodplain and delta. Today, 98% of that sediment remains behind the dam. The result has been a drop in soil productivity and depth, among other serious changes to Egypt's floodplain agriculture (Pottinger, 1996). Now the fertilizing silt is settling in the reservoir instead of being used downstream. Thus the farmland suffers from the depletions that are common to intensively irrigated cropland everywhere. The farming productivity throughout the Nile River Valley and delta is eroded from soil salinization. Before the dam the river brought the natural silt as a buffer against the seawater in the Mediterranean. Now the seawater has intruded as far as 50 km inland and the fertile delta is shrinking. The annual river flow reaching the sea has shrinked catastrophically from 32 to 2 km^3 (or 1000 down to around 60 m^3/s) after the Aswan dam was built. Furthermore, the heavy use and production of fertilizers has put additional demand on the hydroelectric power generated by the Aswan dam and the fertilizer use is bringing heavy pollution to the river and the delta.

The people of Egypt are using the water comparatively efficiently and still the nation consumes almost everything that is available from the Nile. However, with a rapidly increasing population it is easy to realize that the water scarcity will become worse.

Not only Egypt depends crucially on the Nile. Tanzania, Burundi, Rwanda, Kenya, Ethiopia and Sudan are all critically depending on the Nile, as described in Chapter 2.1.

10.4.6 Colorado River basin, USA

The United States is not immune. A report by researchers at the Scripps Institution of Oceanography concludes 'that the growing demand for water in the West, combined with reduced runoff due to climate change, are causing a net deficit of nearly 1.2 km^3 (1 million acre-feet) of water per year in the Colorado River system …' and '… the researchers estimate a 50% chance that Lake Mead could drop too low for energy production (at Hoover Dam) by 2017.'

In 2007 an emergency plan for the Colorado River (Map 10.5) was agreed between the states in the Colorado River basin. The lower basin was promised 7.5 million acre-feet (9 km^3). The total average flow in future years of the Colorado was estimated to 14 million acre-feet (17 km^3). The current daily water level can be monitored on the web (http://lakemead.water-data.com). As of November 2014 the water level is 41 m below the maximum and the Lake is only 40% full. Since June 2014 the water level has varied between 41.1 m and 42.5 m below the maximum level. The climate change models have predicted a 20% decline in rainfall compared to the average of the 1900s.

Map 10.5 The Colorado River basin.

Five new wide-head turbines are being installed at the Hoover Dam. They should keep the power plant working with less water in the lake, even if the water level falls to 305 m. As of November 2014 the level is 329 m, far below the historical average of 358 m. Naturally this will limit the power output from the hydropower station.

The US has in fact stolen the Colorado River from Mexico, using much of the water to irrigate the deserts of Arizona and California. Many tourists come to Las Vegas in the Nevada desert to experience 'an oasis in the desert'. This means green lawns, large golf courses, and fantastic fountains at the large hotels. Even if the golf courses are now watered by reused water the same water could have been used for some farmland further down along the Colorado, or, why not for fishing in Mexico!

10.5 SMALL HYDROPOWER PLANTS

There is no strict definition of what counts as small hydropower. Table 10.5 gives some generally accepted definitions. There is an International Network on Small Hydro Power (INSHP) having about 400 members from 78 countries. The International Center on Small

Hydro Power (ICSHP) is a public and non-profit institution directly under auspices of United Nations Industrial Development Organization (UNIDO), China's Ministry of Water Resources and Ministry of Commerce. ICSHP is headquarters of INSHP and provides information about small hydropower plants (www.inshp.org).

Table 10.5 Definitions of small hydropower plant sizes.

	Size kW
Small hydropower plant	10,000–30,000
Mini hydro	<500
Micro hydro	<100
Pico hydro	<10

Small hydropower plants (SHP) have a long operating life, which has been demonstrated by the successful rehabilitation of numerous projects. Mostly the operating costs are small compared to the upfront capital costs. In large hydro plants the civil works generally takes a higher proportion, while the equipment is the biggest investment in the SHP. This also means that the environmental impact looks different. A small plant will often have other benefits than large ones, such as a greater control over flooding, irrigation, water storage and supply. When SHPs require a reservoir it has been found that they use much more reservoir space per unit of power than larger hydropower plants (see Table 10.2). Typically, micro hydro plants use around 250 hectares per MW while the biggest projects, producing about 3000–18,000 MW, occupy only 10–30 hectares per MW. Small hydropower plants should be considered as complementary to large dams and plants.

10.5.1 Example: Small hydropower in China

About half of all SHP worldwide are located in China, more than 42,000 plants. An SHP offers a decentralized solution to the electric power supply which also means that local grids are mostly used. In China, only 10% of the SHP plants are connected to the national grid and about 50% of them are linked to local grids. The small hydropower plants make up about 30% of the overall hydropower capacity, which implies that around 300 million people rely on this electric power supply. Almost half of the SHP are micro-hydro plants and provide less than 3% of the total SHP capacity. Another 46% are mini-hydro while around 10% of the SHP are within the range of 500 kW to 25 MW but supply around 75% of the electric power output.

It is quite obvious that the operation of small plants does not provide the same kind of challenges as the large ones. The small systems are managed by the local population, and the locals are trained in operation. The equipment is mostly from nearby areas and both maintenance and operation is kept simple. This will of course also influence the overall environmental impact, including water resources, of the hydropower operation. The electrification in villages and rural households is now very close to 100%. It should be noted that the Chinese Government introduced many preferential policies for SHP, such as tax reductions, soft loans/grants from government, encouragement of private firms to invest in SHP stations and policies protecting water supply areas and property ownership.

10.6 INTEGRATED PLANNING

In Chapter 2 we have described some of the conflicts that are caused by dam building. Sometimes the main purpose of the dam is for water storage and other times for hydropower. The World Bank has financed many of the dams in the world, but in the late 1990s the Bank turned skeptical to dam building. The European Union Framework Directive on water policy, published in 2000, has discouraged the construction of new dams, if there are any economically and environmentally viable alternatives. Ledec-Quintero (2003) describe a number of criteria that should be considered in planning of dams, both for hydropower and for other purposes. UNEP (2006) describes the conditions for dams and development projects and aims at having a compendium in possibilities for sustainable dam building.

Hydropower offers a great potential for cost-efficient renewable generation in developing countries with adequate water resources. However, large scale hydropower schemes often have far reaching environmental, social, cultural, technical, financial and economic impacts. Without mitigating measures, these impacts are unevenly distributed, potentially creating both winners and losers. Hydropower projects not only offer the prospects of high rewards but also carry high risks with them. The growing awareness of the impact of dams on natural habitats and the livelihoods of the people affected led governments and donors to gradually curtail funding for hydropower. The World Commission on Dams (an independent body comprising members from governments, the private sector and civil society) developed a set of guidelines that addressed the social and environmental aspects of dams. These guidelines have subsequently been developed further and refined by UNEP, the World Bank and others. If dams are planned, built, operated and, ultimately, decommissioned following the emerging global 'best practices,' hydropower can provide a cost-effective, environmentally sustainable and socially acceptable source of renewable energy.

There numerous cost studies on hydropower plants. For large projects the costs are anywhere between US$ 1,050/kW to US$ 7,650/kW. For smaller projects they are between US$ 1,300/kW and 8,000/kW for smaller projects (IRENA, 2012b). As a comparison, refurbishment and upgrade usually cost between US$ 500/kW and 1,000/kW.

Climate change and competing water needs are impacting hydroelectric power reliability. Drought and competing water demands and priorities are of course changing the availability of water for power. This in turn will impact the power grid support potential as well as the emission benefits of hydropower. These issues are emerging in many countries, including Europe, US and Asia. The dependence of hydro is almost 100% in many countries, so water supply for electrical supply is crucial.

10.6.1 Building hydro dams – a multi-criteria optimization challenge

The design of a hydro dam can be considered as a typical case of multi-criteria optimization. Any cost-benefit analysis has to take several incommensurable factors into consideration.

- Can the income from hydropower compensate for the cost of moving people and using the land?
- What is the benefit of flood control and water storage compared to the cost of losing the fertilizing capability of silt downstream?

- Is there a cost related to the settling of silt and how would the decreasing volume of the reservoir influence the power generation potential?
- Can any silt be removed by dredging or any other method?
- How is the increasing water temperature causing harm to the ecological balance in the river?
- Is the loss of water due to evaporation causing measurable losses for the irrigation of farmlands?
- Is there any increasing risk of unwanted harmful bacteria due to an increasing temperature?
- There may be thermal power plants located downstream from the hydro dam. Will an increased water temperature influence the cooling water capacity for these thermal power plants?

The optimization and the design of the dam for hydropower and water storage surely depend on many factors. Formally we may express the profit/loss of the dam by calculating a performance index (PI) of the form, where some of the α coefficients are positive and others are negative:

$$
\begin{aligned}
PI = {} & \alpha 1 \cdot (\text{net income from hydropower generating capacity}) \\
& \alpha 2 \cdot (\text{value of flood control}) \\
& \alpha 3 \cdot (\text{value for water storage}) + \alpha 4 \cdot (\text{value for recreation}) \\
& \alpha 5 \cdot (\text{value for fishing}) + \alpha 6 \cdot (\text{loss of water due to evaporation}) \\
& \alpha 7 \cdot (\text{cost for moving people, villages and towns}) \\
& \alpha 8 \cdot (\text{cost for decreasing dam volume due to silt settling}) \\
& \alpha 9 \cdot (\text{cost for losing silt downstream}) \\
& \alpha 10 \cdot (\text{cost for increasing flow speed}) \\
& \alpha 11 \cdot (\text{cost for dredging silt}) \\
& \alpha 12 \cdot (\text{ecological and environmental costs due to an increasing temperature}) \\
& \alpha 13 \cdot (\text{cost for health dangers from water borne diseases})
\end{aligned}
$$

In the calculation of the net income of the hydropower generation the costs for transformers, switch yards and power transmission have to be taken into consideration. The cost for transmission is often a major cost since hydropower generation may be located in remote areas, far from the potential consumers. Then this calculation may compare the cost for alternative power plants located closer to the population centres.

There is no objective way to give a value to the weighting factors α. Rather their relative sizes are determined by political, organizational, economic and other subjective factors. This of course means that the outcome of the real cost/benefit analysis is truly subjective, depending on which value that is given to each one of the expected consequences.

A sensitivity analysis will reveal the importance of various terms. How would the performance index change as a result of future electrical power rates? Will any probable climate change influence the flow rate of the river or its temperature? How is the PI influenced by giving different values of ecological consequences?

Multicriteria decisions and integrated planning is a necessity in complex hydro dam projects.

The calculated life span of the reservoir has to take the silt accumulation into consideration. Is the real cost/benefit calculated for the most probable life span of the system? It is apparent that future hydropower issues have to be addressed in an inter-disciplinary, and at least at river basin level. Stakeholders, including political leaders to the civil society and water users have to be included in the planning. The cost of non-cooperation is huge. Still hydropower is attractive compared to some alternatives. In contrast to nuclear power, hydropower leaves no toxic waste to threaten future generations, and in contrast to thermal power it emits virtually no greenhouse gases, once it has been put into operation (but there are exceptions, as discussed in Chapter 10.3).

10.6.2 Guiding towards sustainability

A large number of social and environmental non-government organizations (NGOs), governments, banks together with the International Hydropower Association (IHA) formed the Hydropower Sustainability Assessment Forum in 2008. The Forum developed a Protocol by 2011 (www.hydrosustainability.org), available for all parties without charge (see also IHA (2012)). Many of these organisations are now represented in the Hydropower Sustainability Assessment Council. The Hydropower Sustainability Assessment Protocol is a tool that promotes and improves the sustainable use of hydropower. It provides a common language that allows governments, civil society, financial institutions and the hydropower sector to talk about issues of sustainability. Assessments are based on objective evidence and the results are presented in a standardized way, making it easy to see how existing facilities are performing and how new projects are being developed.

The protocol should help people to look for synergies and trade-offs between economic, social and environmental values, in other words to help in integrated planning. The topics to consider are summarized in the Table 10.6. The full protocol is available on the website www.hydrosustainability.org and contains more than 200 pages.

Table 10.6 Topics addressed during an assessment of hydropower.

Cross-cutting	Environmental	Social	Technical	Economic/ Financial
Climate change	Downstream flow regimes	Resettlement	Siting and design	Financial viability
Human rights	Erosion and sedimentation	Indigenous peoples	Hydrological resource	Economic viability
Gender	Water quality	Public health	Infrastructure safety	Project benefits
Livelihoods	Biodiversity and invasive species	Cultural heritage	Asset reliability and efficiency	Procurement

Source: www.hydrosustainability.org.

The International Hydropower Association (IHA, www.hydropower.org) Sustainability Guidelines state that hydro developers planning a project should try to minimize the following (IHA, 2012, 2014):

- Health dangers, particularly from water-borne diseases or malaria;
- Loss of homes, farms and other livelihoods;
- Disruption of community networks and loss of cultural identity;
- Changes to biodiversity in the affected area.

They should try to maximize the following:

- Timely consultation at all levels;
- The flow of relevant information to all those affected;
- Negotiated settlement of disputes;
- Timely and adequate payment of any compensation.

Where people or communities have to be transferred to new sites, developers should do the following:

- Investigate possible alternative ways of doing the project;
- Ensure adequate consultation with the people to be displaced throughout the project;
- Guarantee equivalent or improved livelihoods at the new location;
- Provide better living standards and public health at the new location.

Rapidly developing countries such as China, India and Turkey frequently argue that their electricity requirements for economic growth and social development outweigh the environmental concerns surrounding hydropower, and that support for large hydropower development is a pro-poor policy. However, several non-governmental organizations are campaigning to have large hydropower excluded from global efforts to promote renewable energy. Among the arguments advanced for this position are the following:

- Including large hydro in renewables initiatives reduces the available funding for new renewable energy technologies;
- There is no technology transfer benefit from large hydro, which is a mature technology;
- Large hydro projects often have major social and ecological impacts;
- Large reservoirs can emit significant amounts of greenhouse gases from rotting organic matter;
- Large hydro reservoirs are often rendered non-renewable by sedimentation.

This long-standing debate is still a major issue. Many large hydropower projects necessitate the construction of large dams. These are structures with a long life, which permanently alter the river downstream and affect a significant stretch of the river upstream. They are not, strictly speaking, renewable. However, there are also large run-of-river hydropower projects, as well as small, mini and micro hydropower projects, which are all renewable energy providers. It must also be remembered that the primary driving force for much new dam construction is irrigation rather than hydropower generation.

One way to better understand the water/energy nexus is to distinguish the issue of large dams from that of hydropower. In all these cases, greater transparency, accountability and oversight of the contractual process to ensure the exposure of corrupt practices are all necessary in order to promote social equity and good governance.

In developing countries where affordable power is desperately needed, environmental concerns must be carefully weighed against urgent development needs. Governments will be less responsive to objections to the construction of dams for large hydropower generation or to the deployment of new, greenhouse gas-emitting coal-fired power plants, when their priority is meeting rapidly growing electricity demand. Clearly, the transition to a fully sustainable, global energy supply system needs cooperative and innovative, if not radically new, policy-making.

10.7 CHAPTER SUMMARY

Hydropower and dam building are meant for

- Electric energy generation,
- Flood control,
- Water storage for irrigation, drinking and industrial use, and
- Navigation.

Hydropower generation has a lot of attractive features using renewable water, having hardly any greenhouse emission and being most useful for grid operations. However, any dam building has several negative consequences that have to be considered in the planning and the price for hydropower. In hot climates the evaporation is a huge problem. The silt that is trapped will shorten the life span of the dam system. Any operation of a hydropower system has to balance between power generation and flood control. Integrated planning is crucial if the positive values are to be maximized and the negative consequences minimized.

10.8 MORE TO READ

There is a lot of literature on dams and their environmental impact. The books by Fradkin (1996), De Villiers (2001), Solomon (2010) and Pearce (2006) are excellent documents. Reisner (1986) lists several cases where the life span of the dam has been drastically reduced as a result of silt collection. Theroux (1997) tells about the destruction of the Nile Delta. Sources of the Chinese dams are from the China Daily newspaper. National Geographic presents the Three Gorges and the Yellow River for a broad public (Zich-Sacha, 1997; Larmer-Girard, 2008). Kolars-Mitchell (1991) and De Villiers (2001) inform about the Euphrate-Tigris rivers.

The report IEA (2002) gives an overview of the environmental impacts of electricity generation using different technologies.

11 Fossil fuels

Burning buried sunshine – consuming ancient solar energy.
Title of paper, Dukes (2003).

As remarked in Chapter 9 the overall evolution of the global energy mix appears to remain in a relatively fixed path; continued reliance on fossil fuels. Fossil fuels are mainly oil, coal and natural gas. The share today of fossil fuel in the global mix is 82%, the same as 25 years ago (IEA, 2013a). Even if a strong rise in the use of renewables IEA predicts that in 2035 fossil fuel share will be reduced only to 75%.

Burning fossil fuels means that we release carbon in the atmosphere that has been bound in the earth for millions of years. Of all the carbon released from the fossil fuels (2011) about 44% come from coal, 35% from oil and 21% from natural gas. It is important to realize that the carbon release is not proportional to the amount of fuel burned. It depends on the carbon content of the fuel. One ton of pure carbon will release 3.7 tons of CO_2 (see Chapter 4.5). Oil derived fuels are less rich in carbon with two hydrogen atoms for every carbon atom in the structure. Hydrogen is a source of energy and produces the heat when burned with carbon. Therefore oil releases less CO_2 per unit than coal. Methane, CH_4, has only one carbon atom for every four hydrogen atoms and has the smallest CO_2 release. Consequently there is a big difference from a climate perspective which kind of fossil fuel is used. Using the highest quality of coal – anthracite – to generate electrical power will release about 67% more CO_2 than burning methane. Brown coal (lignite) will produce 130% more emission than methane.

Unlike coal, natural gas produces hardly any toxic air pollutants like sulfur dioxide (SO_2) and mercury when burned – so the transition from coal-fired to natural-gas-fired electricity generation is improving overall air quality, which improves public health. Though natural gas burns cleaner than coal, uncombusted natural gas is mostly methane with a GWP-20 of 84 (see Table 4.2).

The carbon footprint of a fossil fuel depends on its carbon content.

An interesting way to measure our resource use is to calculate how much solar energy and organic material was needed millions of years ago in order to create our fuel. It is estimated that about 100 tons of ancient vegetation is needed to produce 4 liters of petrol. To cite Dukes (2003): it took the solar energy of more than 400 years to provide sufficient energy that was consumed in one year, in 1997.

We listed the water footprints of the various fossil fuels in Chapter 9. Here we will look more at the processes and the background for the water quantity and water quality footprints of the various industries. The fossil fuel industry is particularly responsible not only for the water footprints but also for unpurposeful use of water from leakages, dredging and refining.

It becomes apparent that fossil fuel extraction and refining is closely related to human rights. One aspect is violations of the right to water – which occur when oil spills and waste materials pollute water aimed for drinking, fishing, agriculture or other domestic purposes.

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission *increase* from 1970 to 2010, with a similar percentage contribution for the period 2000–2010 (IPCC, 2014b, Ch. 1.2 and 5.2). Fossil fuel-related CO_2 emissions grew by about 3% between 2010 and 2011 and by 1–2% between 2011 and 2012. Fossil fuel will dominate among the energy sources for a foreseeable future. One reason is that fossil-fuel subsidies continue to distort energy markets. The global cost of fossil-fuel subsidies expanded to US$ 544 billion in 2012 despite efforts at reform (see further 11.9). Financial support to renewable sources of energy totaled US$ 101 billion (IEA, 2013a, Chapter 6). Annual worldwide capital expenditure on oil, gas and coal has more than doubled in real terms since 2000 and surpassed US$ 950 billion in 2013 (IEA, 2014a). It should be emphasized that coal is the cheapest energy source, and investment in coal supply is much less expensive per equivalent unit of output than oil or gas. Still cheaper is it to emit all the CO_2 from the smokestacks. Carbon can be dumped into the atmosphere without any cost in most places.

There is no shortage of national, even global, targets for renewable energy deployment (such as 30% of all electricity from wind by 2030, 50% of all energy from non-fossil sources by 2050), but these are, at best, aspirational goals and not realistic aims. Between 2000 and 2010, global output of renewable energies grew by 2% but that of fossil fuels by 2.65%. During the first decade of this century the world has been running into fossil fuels, not away from them, a reality that will not change rapidly. And while the contributions of wind and solar PV more than tripled during that decade, the world is now more dependent, in both absolute and relative terms, on fossil-fuelled generation than it was in 2000 (WEF, 2013).

Conventional oil and gas are discussed in 11.1. This type of oil and gas is what we have traditionally used. Conventional oil and gas resources are reservoirs of natural gas or oil that typically permit the oil and natural gas to flow readily into wellbores. In 11.2 the shale gas ‘revolution’ is described and the water usage is analyzed. Shale gas is natural gas that is trapped within shale formations. Shales are fine-grained sedimentary rocks that can be rich sources of petroleum and natural gas. Drilling technology development in combination with hydraulic fracturing (see Glossary), often called ‘fracking’, has made it possible to extract the shale gas and oil at competitive prices. Oil and gas exploration, however, come with a cost: accidents and spills. This is discussed in the following sections 11.3–11.5. Oil accidents and large spills are described from North America, Nigeria and Russia respectively. Natural gas is also burned as a waste gas. Enormous amounts of excess gas are flared, as reported in 11.6. Another unconventional kind of oil is what is found in oil sand. As described in 11.7, the water use for oil sand exploration is much larger than for conventional oil. Not all the natural gas found is used. Coal is still the dominating fossil fuel, and the water and environmental consequences of coal mining and burning are outlined in 11.8. The relation between climate and fossil fuels was illustrated in Chapter 4 and in 11.9 further couplings between climate and fossil fuels are discussed. The chapter is summarized in 11.10.

11.1 CONVENTIONAL OIL AND GAS

> *‘Energy forecasting is easy. It’s getting it right that’s difficult’*
>
> – Graham Stein, 1996

There is a tight connection between water and oil. As oil is the world's principal transportation fuel, it is easy to overlook the connections between it and water. Oil is at the center energy-security concerns for most nations and regions. Oil products provide over 90% of transport energy in almost all countries. As a result, oil supply interrupts may have serious effects, not only on mobility, but also on food production and distribution, heating, medical care, national security, manufacturing, and other vital functions of modern societies.

Petroleum is strictly the same as crude oil. However, often all liquid, gaseous, and solid hydrocarbons are called petroleum. Lighter hydrocarbons – methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}) – occur as gases under surface pressure and temperature conditions, while pentane (C_5H_{12}) and heavier hydrocarbons appear as liquids or solids. In an underground oil reservoir the proportions of gas, liquid, and solid depend on pressure and temperature. The petroleum industry generally classifies crude oil by the geographic location it is produced in, its density (called API gravity by the industry), and its sulfur content. A light crude oil has a low density and a heavy crude oil has a high density. A strict definition of different oil quality terms is found in Table 7.4 of the Global Energy Assessment report (GEA, 2012). Depending on the quality of the oil (API gravity), the location (inland, offshore), or depth of the deposit, recovery methods are more or less water and energy intensive.

An oil well produces predominantly crude oil, with some natural gas dissolved in it. Because the pressure is lower at the surface than underground, some of the gas will come out of solution and be recovered (or burned). This is called *associated gas* or *solution gas*. A gas well produces predominantly natural gas. The gas may contain also heavier hydrocarbons, because the underground temperature and pressure are higher than at the surface. The molecular composition of oil varies widely from well to well, but the proportional of chemical elements vary over fairly narrow limits. The dominating elements are carbon (83–85%) and hydrogen (10–14%). As remarked in the introduction, this corresponds to about two H atoms for every C atom.

Crude oil is also found in semi-solid form mixed with sand and water, as in the Athabasca oil sands in Canada, where it is usually referred to as crude bitumen. Bitumen is a sticky, black, tar-like form of crude oil which is so thick and heavy that it must be heated or diluted before it will flow (see Section 11.7). Venezuela also has large amounts of oil in the Orinoco oil sands, although the hydrocarbons trapped in them are more fluid than in Canada and are usually called extra heavy oil. These oil sands resources are called *unconventional oil* to distinguish them from oil which can be extracted using traditional oil well methods. Between them, Canada and Venezuela contain about twice the volume of the world's reserves of conventional oil.

11.1.1 Oil and gas resources

It is recognized that hydrocarbon resources are huge compared with conceivable future energy needs (GEA, 2012; IEA, 2013a). It is also true that to extract these available resources will require not only major investments but will have significantly devastating consequences for a sustainable future (IEA, 2014a). (It is interesting to follow the discussions among pension funds. The 4th AP Pension Fund in Sweden requires that there should be a law that forces the funds to declare the climate impact of the investments.)

We have already seen (Chapter 4) that fossil fuels have a dramatic influence on the climate. The extent of ultimately recoverable oil and natural gas has been subject to numerous reviews, and there are wide ranges of estimates in the literature. For example, figures between 4900 and 13,700 exajoules (EJ, 10^{18} J, see App. 1.2) for conventional oil reserves and resources have caused continued debate and controversy (GEA, 2012). There are varying boundaries of what is included in the estimates, for example conventional oil only or conventional oil plus oil shale (see 11.2), tar sands (11.7), and extra-heavy oils.

Recent estimates of conventional oil reserves are reported in Table 7.5 of GEA (2012), where 8 different sources have been cited. The estimates of the world total reserves vary between 116.3 Gt (10^9 tons) (Energy Watch Group) and 181.7 Gt (BP). Some estimates include reserves of oil sands, which are defined as unconventional oils. The low estimate of the Energy Watch Group stems from their suspicion that the reserve data reported by the governments of the Middle East are politically motivated and hence unrealistically high. The largest conventional oil reserves, according to BP, are listed in Table 11.1.

Table 11.1 Conventional oil reserves, expressed in EJ (exajoule, 10^{18} J).

Middle East	4308
Latin America and Caribbean	1203
Former Soviet Union	704
Northern Africa	389
Western and Central Africa	263
Canada	189
U.S.	162

Source: GEA (2012), Table 7.6.

It is important to understand the distinction between the terms ‘resources’ and ‘reserves’. The first refers to the oil and gas that may exist in an area, whereas the second is the amount that may be practicably recoverable. (The vocabulary is interesting: the meaning of the word is that ‘if something is *recoverable*, it is possible for you to get it back’. Did the oil and gas belong to humanity from the beginning?) The amount of reserves depends on geology and technology but also on political and social aspects. In statistics there is often confusion since various sources use different definitions. For example, reserves reporting in the US require a 90% probability of recovery under existing economic, technological, and political conditions. Other sources typically declare reserves at a median, 50%, probability. Whatever the definitions the reserve estimates have increased over time. The price of oil will determine what becomes economically recoverable, so even if the oil or gas would be technically recoverable it may stay below ground as long as the price is not right. Figure 11.1 illustrates the petroleum consumption in the 8 biggest consumer countries. The per-capita consumption shows another picture.

The International Energy Agency (IEA) predicts that estimates of ultimately recoverable resources of oil will continue to increase as technologies unlock types of resources, such as light tight oil (see 11.2), that were not considered recoverable only a few years ago (IEA, 2013a). IEA also predicts that the oil supply will rise from 89 million barrels/day (mb/d) in 2012 to 101 mb/d in 2035. Key components of the increase are unconventional oil (up 10 mb/d) and natural gas liquids (NGLs) linked to the increase in global gas output (up 5 mb/d). Conventional crude oil’s share in total oil production falls, from 80% in 2012 to two-thirds in 2035. The US is expected to be the world’s largest oil producer for much of the period to 2035.

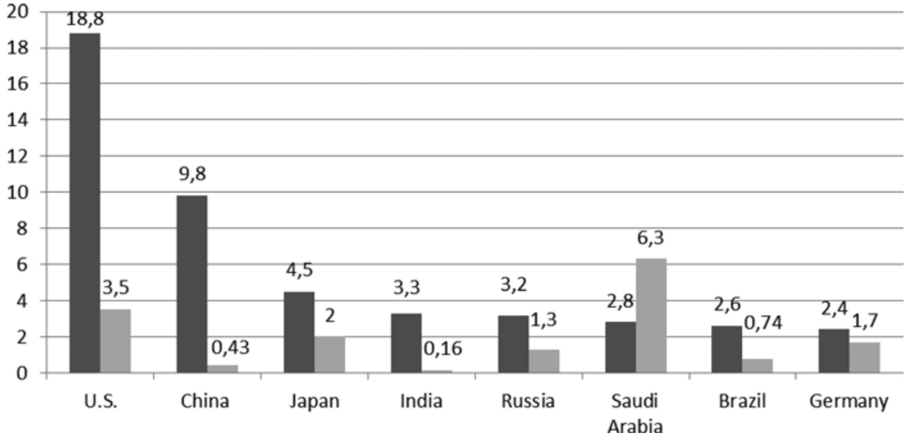


Figure 11.1 Petroleum consumption (2011) in the countries with the biggest total consumption measured in million barrels per day (mb/d), left dark column (1 mb/d = 0.159 million m^3). The right (grey) column shows the consumption per capita (m^3/year). (*Source*: CIA (2011)).

> *Oil and gas supply will continue to increase at least until 2035.*

Oil production from areas that are difficult to access or from unconventional resources is not only more energy intensive, but also technologically and environmentally more challenging. The production of oil from tar sands, shale oil, natural gas from shale gas or the deep-sea production of conventional oil and gas raises further environmental risks, ranging from oil spillages, groundwater contamination, greenhouse gas (GHG) emissions, and water contamination to the release of toxic materials and radioactivity. A significant fraction of the energy gained needs to be reinvested in the extraction of the next unit, thus further exacerbating already higher exploration and production costs.

11.1.2 Water for conventional oil and gas extraction

Oil exploration is an expensive, high-risk operation. Once a well has been found and verified a drilling operation will be performed to finally make the final decision of exploration or not. A typical well on a continental shell, like in the North Sea, would cost US$ 10–30 million while a deep-water well can cost US$ 100–200 million. It only has a one-in-four chance of success on average. To search for petroleum on-shore is not as costly and some wells may cost only some US$ 0.1 million per well.

> *Oil exploration has a huge water footprint – not only a carbon footprint.*

Water is needed for the extraction of oil from underground sources as well as for the refining of the crude oil. Most new commercial oil and gas wells are initially free flowing, so that the underground pressures drive the liquid and gas up the well bore to the surface. The rate of flow depends on a number of factors such as the properties of the reservoir rock, the underground pressures, the viscosity of the oil, and the oil/gas ratio. To drill wells requires water for preparing drilling fluid: cleaning and cooling of the drill bit, evacuation of drilled rocks and sediments, and providing pressure to avoid collapse of the well. Gleick (1994) estimates that less than 0.1 liter of water is needed for every liter of crude oil (0.6 gallons per MMBTU; for conversion, see App. 1 and 2) for drilling. Drilling fluid contains potential contaminants and must be treated to separate excavated material and dissolved species.

Oil and gas reservoirs have a natural water layer (called formation water) that, being denser, lies under the hydrocarbons. Oil reservoirs frequently contain large volumes of water, while gas reservoirs tend to contain only small quantities of water. In order to maintain the reservoir pressure it is common to inject gas, water, or steam into the reservoir. In some cases, the oil may be too heavy to flow. A second hole is then drilled into the reservoir and steam is injected under pressure. The heat from the steam thins the oil in the reservoir, and the pressure helps push it up the well. The most common extraction method is secondary oil recovery through water flooding and mechanical pumping. For the secondary recovery much more water is used for oil extraction, around 8 liters of water per liter of oil (62 gal/MMBTU).

Crude oil extraction may require anywhere between 0.1 and 8 liters of water per liter of oil.

Oil is often located in geological formations with large volumes of water with high salt concentrations. Khatib-Verbeek (2003) estimated that three times more water than crude oil is ‘produced’ in oil extraction. However, there is very high variability in these figures from one location to another; some wells producing as much as 20 times more water than oil. The ratio of produced water (see Glossary) to crude oil usually rises as the wells age. Produced water can contain hydrocarbon residues, heavy metals, hydrogen sulfide (H_2S) and boron, as well as high salt concentrations (NRC, 2010). Traditionally, oil producers disposed of this waste directly into the environment or into evaporation pits. Today, most oil producers re-inject produced water or reuse it for onshore wells (98%). However, 91% of produced water from offshore wells is simply discharged into the ocean (Clark-Veil, 2011).

The ratio of water-to-oil is interesting for our purposes. Early in the life of an oil well, the oil production is high and water production is low. Over time the oil production decreases and the water production increases. The ratios are estimated:

- Worldwide estimate – 2:1 to 3:1;
- US estimate – 5:1 to 8:1. Many US fields are mature and past their peak production (Clark-Veil, 2011). The ratio may be even higher: many older US wells have ratios >50:1;
- Once crude oil has been extracted, it must be separated into its different constituents before use. Water consumption in a refinery depends on its design and on the type of oil that it is refining. Wu *et al.* (2009) have estimated the water-oil ratio between 1:1 and 2:1 for crude oil (7.2–13 gallons of water per MMBTU). Newer facilities are more water efficient and are often at the lower end of this range.
- After refining, petroleum products continue to affect water quality during transport and storage. In the US, the EPA has recorded more than 490,000 confirmed leaks from underground storage tanks for petroleum products (Allen *et al.* 2011). Some major oil accidents and spills in the world are discussed in Chapter 11.3–11.5.

The ratio between water 'production' and oil production can be anywhere between a fraction of a liter to more than 50 liters of water per liter of oil.

11.2 SHALE GAS – A 'REVOLUTION'

> *'My formula for success?'.... ...'Rise early. Work late. Strike oil.'*
> J. Paul Getty (1892–1976)

Over the last several years the production of unconventional shale gas (see Glossary) in the United States has dramatically increased from 1% of natural gas supplies in 2000 to some 30% in 2011 and is projected to increase to 64% in 2020. Unconventional gas is the collective term used for shale gas, tight gas and coal bed methane (CBM). There is nothing unconventional or unusual about the gas itself; rather the rocks in which the natural gas is trapped are unique. In 2008 almost $60 \cdot 10^9$ m^3 (≅2 trillion cubic feet) of gas was produced in the US. In 2012 the production had increased a factor of 4. This has been heralded as the 'shale gas revolution,' with significant implications for energy security not only in the US but also in the rest of the world. When applying to the US case, adding shale to other natural gas consumption and considering the annual national consumption rate of natural gas, current reserves would last for the next 100 years, according to Department of Energy's independent statistics agency, the Energy Information Administration (EIA, 2013). The total amount of the world's technically recoverable gas resources would increase more than 40% if all the shale gas resources were added to the already identified conventional gas resources. Though global in focus, most references in this chapter are made with regard to the US and its shale gas industry. The reason is that shale gas operations in many regards have come much further in the US than in any other country. Consequently, most of the impacts can be observed and analyzed there.

As a natural gas and fossil fuel, shale gas burns cleaner than other fossil fuels. This has prompted some to call it 'clean', but this is of course not the case. In fact shale gas produces GHG both in combustion as well through leakage in extraction processes. CO_2 and the very potent GHG methane are prevalent components in shale gas. Science is still in the process of determining climate impacts posed by increased production and usage of shale gas. Some scenarios suggest that shale gas could in the short term offer some value in possibly replacing more CO_2 intensive fuels (mostly coal) to provide a transition in order to increase usage of CO_2 neutral renewable energy. Such a scenario would then demand that shale gas itself would quickly be phased out and replaced by renewables (mostly wind and photovoltaic) if not to constitute a net negative on GHG contributions to the atmosphere and thus a catalyst in water related climate change effects.

11.2.1 Shale gas – a 'tight' gas

Producers have long known shale as 'source rock' – rock from which oil and natural gas slowly migrated into traditional reservoirs over millions of years. Oil extraction has traditionally come from conventional reservoirs. Shale gas, sometimes called 'tight gas', refers to sources of natural gas (almost entirely methane) that are locked in layers of impermeable hard rock (shale formations). Over time these layers have been exposed to high pressures and temperatures and compressed, leading to decomposition of entrapped organic material and recrystallization and cementation of the material between generated pockets of gas. Oil shale deposits can be considered as an immature oil field. This waxy substance has to be extracted from the rock, upgraded to synthetic crude oil and refined before it can be used commercially. The shales that are a main source for hydrocarbons are known as black shales because of their color and organic content. Their pores are typically filled with 2–18% by weight of carbon in organic compounds (Turcotte *et al.* 2014).

The gas is trapped in small pores in the shale formations. Rock layers below the surface are stacked on top of each other like pancakes. The shales are sedimentary rocks with a very low permeability coefficient ($<10^{-12}$ m/s), meaning that the rock is very tight and compressed. The gas can very slowly migrate (during hundreds of thousands of years or even million years) from the matrix into a reservoir. Oil explorers in the US had often drilled through shales on their way to even deeper sedimentary rock formations. When they passed through such a shale they often noticed gas 'shows', indications that the rock likely held large amounts of natural gas. However, it looked too hard and expensive to extract gas from this tight rock far below the ground.

11.2.2 Technology for shale gas exploration

In order to reach the gas in the shale, new technology had to be developed. The conventional vertical drilling will miss most of the shale gas, since most of the gas trapped in a shale will not easily flow to a 'wellbore', the hole drilled into the ground to create a well. One groundbreaking technology achievement was the combination of vertical with ***horizontal drilling***, where the drill at depth (typically around 3,000 m) can be turned 90° to access horizontal shale layers where large amounts of natural gas and oil that are usually trapped can be released by shattering the shale. The horizontal drilling was perfected through years of trial and error.

The technique was unusual until the 1980s when operators in Texas began completing thousands of horizontally-drilled wells drilled at the bottom of conventional vertically-drilled wells. The first horizontal well was drilled in the Barnett shale in North Texas in 1991 and then applied more effectively in 1997 by George P. Mitchell, often referred to as the 'father of fracking' (Zuckerman, 2013). Some major advantages brought by horizontal drilling are for instance that wells under areas not suitable for drilling can now be reached from afar. Then the 'payment zone', that is, the area from which gas can leak trough a bore hole, can be increased. It also increases opportunities to hit a maximum number of fracture zones. On top of the drilling technology three-dimensional seismic imaging was used for mapping the shale areas.

The other key technology to make shale gas economically feasible was the development of ***hydraulic fracturing***. The dense rock simply had to be broken up in order to reach the trapped oil in the pores of the rock. Artificially stimulating the flow of hydrocarbons from a well is not new. The earliest attempts to do so in the US date back to the 1860s, and involved lowering explosive charges down the boreholes of oil wells. The first experiments with hydraulic fracturing took place in 1947. Already in 1949 the first commercial applications of the technique were carried out for oil exploration in Texas and Oklahoma by the company Halliburton. As of 2012, 2.5 million hydraulic fracturing operations had been performed on oil and gas wells worldwide, more than one million of them in the US. Hydraulic fracturing in combination with horizontal drilling made the US shale gas 'revolution' possible. Fracking will widen the existing cracks by pumping water mixed with proppants (mostly sand) and chemicals under high pressure.

> *The combination of horizontal drilling technology and hydraulic fracturing has revolutionized the shale gas extraction.*

11.2.3 Shale gas resources

What is remarkable about natural gas released by fracking is the huge amount of it that is potentially available. Natural gas resources that were known but considered unreachable suddenly became available for commercial purposes, creating what can be labeled a 'new natural gas era'. The natural gas from shale gas will have a lot of implications. Replacing coal with natural gas for power production will decrease the carbon footprint. However, if shale gas merely displaces efforts to develop cleaner, non-carbon, energy sources without decreasing reliance on coal, the doom and gloom of more rapid global climate change will be realized. Shale gas will certainly change the geopolitical map, since it will be available in several countries. The discussion on 'peak oil' will change.

Two-thirds of the assessed, technically recoverable shale gas resource is concentrated in six countries – China, Argentina, Algeria, US, Canada and Mexico (EIA, 2013). The top ten countries account for over 80% of the currently assessed, technically recoverable shale gas resources of the world, Figure 11.2. Similarly, two-thirds of the assessed, technically recoverable shale oil resources are concentrated in six countries: Russia, US, China, Argentina, Libya and Australia. Texas accounted for nearly one third of both crude oil and natural gas reserves in the US in 2012. To date most shale gas formations have been found onshore in many countries. Actually, the World Resources Institute estimates that 386 million people live on the land above shale gas resources (WRI, 2014).

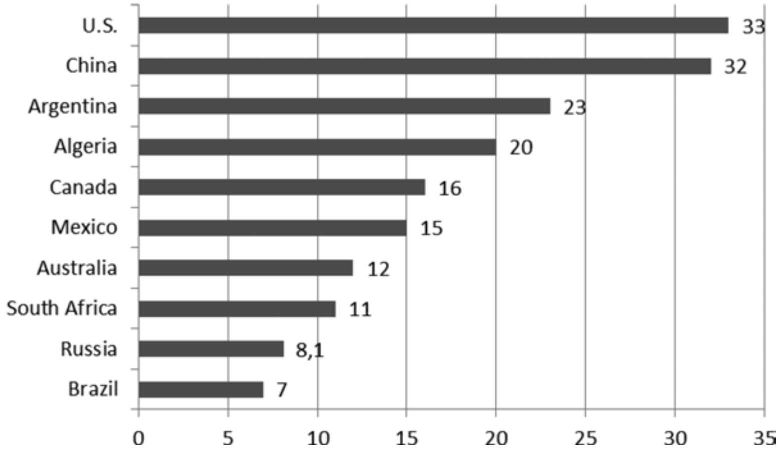


Figure 11.2 Top 10 countries with technically recoverable shale gas resources (10^{12} m^3). Europe (including Russia) has 25×10^{12} m^3 and the world total is 221×10^{12} m^3. The current annual global consumption of natural gas is about 3.4×10^{12} m^3. (To convert the volumes to trillion cubic feet – Tcf – multiply with 35.25.). (*Source*: EIA (2013), Table 2).

Since it is extremely difficult to visualize these large numbers, let us compare the shale gas resources with electrical power consumption. In 2011 the world produced 22,126 TWh of electrical power (last available data from IEA, 2013b). The energy content of natural gas

(Appendix 2) is 0.036 MJ/liter or 10 kWh/m^3. Thus, the global consumption of natural gas corresponds to 34,000 TWh. So, assuming 50% efficiency in the power plants the current natural gas consumption can satisfy around 75% of current electrical power need. The total shale gas resources of 221×10^{12} m^3 can provide all electrical power (assuming 50% power plant efficiency and the 2011 consumption) for the world for almost 50 years. The report EIA (2013) estimates the total (in the hope of a favorable outcome) shale gas in-place of 880×10^{12} m^3 (31,138 Tcf), four times the technically recoverable shale gas.

The annual production of natural gas would be sufficient to supply around 75% of the current electrical power need.

The development of shale gas extraction started in the US while other countries still today are at the start blocks. Massive oil and natural gas resources have given North America hopes of becoming what some call ‘Saudi America’ and have made the US much less dependent on the import of oil and even an oil and gas exporter.

The commercialization of formerly unconventional tight and shale gas deposits in the US was largely led by small and medium size energy companies, and significantly changed the supply security of the US gas market. These companies were led by ‘wildcatters’ – a combination of gamblers, hopeless dreamers, geologists and entrepreneurs – who took a chance of drilling in shale. By 2010 the big oil and gas corporations had taken notice of the US energy revolution with the potential to make US independent of foreign oil. In 2011 and 2012 BP, Statoil (Norway) and Total (France) each spent billions of dollars for acquisitions and joint ventures around the US. Also the China National Offshore Oil Corporation, Eni (Italy) and BHP Billiton (Australia) did the same. The American Exxon made its biggest deal in a decade and paid US$ 31 billion to buy the natural gas driller XTO Energy. This made Exxon the largest natural gas producer in the US (Zuckerman, 2013, p. 320).

Europe is rich in shale gas reserves. However, Europe has a high population density and more restrictive rules than the US regulating how to explore for oil and gas. Relatively less experience exists in Europe for shale formations as new source of natural gas. The European Commission initiated a study to analyze how the relevant applicable European legal framework, including environmental law, is applied to the authorization and operational permitting for prospection, exploration and production (Philippe & Partners, 2011). No commercial scale shale gas exploitation has taken place yet. The gas dependency is viewed differently in different European countries. Poland and the Baltic States wish to become energy independent of Russia, more so given recent developments in Ukraine. Although Poland has always been apprehensive about its dependence on Russian gas, it has issued nearly 25% of the shale gas exploration permits to Russian companies (World Energy Council, WEC, 2013). With an established onshore conventional oil and gas production industry as well as recent experience with coalbed methane exploration, Poland offers Europe’s best prospects for developing a viable shale gas/oil industry (EIA, 2013). Poland’s shale industry is still at an early exploratory, pre-commercial phase. On the other hand, Hungary, France, Bulgaria, and parts of Spain have already banned hydraulic fracturing, concerned about the environmental risks.

In UK there is a large interest in the shale oil and gas resources (Fracking UK, 2014). Indications so far are that the country has enough recoverable shale gas to completely replace its gas imports for more than a century. The Government has claimed in 2014 that UK ‘needs to cut energy costs’. The Government will be ‘investing in a shale gas revolution’. Michael

Fallon, the Energy Minister, have stated that 'shale gas is important to the UK's energy security of supply. UK has issued a number of shale gas exploration permits. Russia's dealings with the Ukraine have exacerbated this.' (BBC News 23 May 2014). Despite this shale exploration has not yet taken off as it has done in the US, and investment has so far been modest. There are many suggested reasons for this. One reason is that in UK underground mineral rights do not belong to the landowner, as they often do in the US, but to the British Government. Probably the main reason why activity has been restrained so far is resistance from local populations and policymakers. People are afraid that fracking will destroy the landscape, pollute drinking water aquifers and cause earthquakes.

In parallel the role of shale gas can also be viewed in a European context of existing strategies to move away from other more CO_2 emissive fossil fuels while striving to increase renewable energy in the energy mix. An expansion of shale gas could potentially also mean substantial cuts in energy prices and new job opportunities. There are some signs to suggest that the EU might be paving the way for increased deployment of shale gas. In a March 2014 vote, the European Parliament adopted a new environmental law imposing stricter rules on assessing and disclosing environmental impact of oil and conventional gas exploration. However this could only be done if exemption was made for shale gas (deemed as an 'upstream' energy source), largely attributed to effective lobbying from Poland and the United Kingdom (Reuters, 2014).

There is no doubt that natural gas extraction does sometimes have negative consequences for the local environment in which it takes place, as does all fossil fuel extraction. And because fracking allows us to put a previously inaccessible reservoir of carbon from beneath our feet into the atmosphere, it also contributes to global climate change.

11.2.4 Water use in hydraulic fracturing

The two primary water issues associated with fracking are:

- the use of a large amount of fresh water that becomes contaminated and which can never again be used by humans, animals or plants for any purpose, and
- the necessity of protecting underground water tables and surface water resources from contamination by fracking fluids and/or migrating gas deposits.

Water availability is crucial for fracking. The risk associated with water scarcity as well as with water quality has to be considered carefully. There is a risk of leakage from improperly treated produced water and fracking fluids from flowback into the soil and water table. Often the shale gas is found in dry areas. Although the overall water use for shale gas and hydraulic fracturing is low in comparison to other users (such as cooling water for thermal power plants, see Chapter 13), in some water-scarce areas water use for shale gas constitutes a large fraction of groundwater resources and could lead to potential water shortage. While the economic driving forces are huge the environmental consequences of shale oil and shale gas and the impact of hydraulic fracturing on air and water quality are intensely debated.

Shale resources are unevenly distributed worldwide and, for the most part, not located where freshwater is abundant. The World Resource Institute (WRI, 2014) has found that lack of available water can restrict shale development in many regions around the world. For example:

- 38% of shale resources are in areas that are either under high to extremely high levels of water stress (see Glossary) or are arid;
- 19% are in areas having high or extremely high seasonal variability.

Figure 11.2 shows that China, Mexico, South Africa as well as the US are rich in recoverable shale gas but all of them face high to extremely high water stress where the shale is located.

After the vertical and the subsequent horizontal drilling have been completed and the casings are in place, the casing in the horizontal leg of the wellbore is perforated. Pressurized fracturing fluid is injected into the wellbore and through the perforations to crack the shale rock and release the natural gas. The fracking fluid can be injected at various pressures and reach up to 100 MPa (≅1000 bar) with flow rates up to 265 liters/second. The produced cracks extend 50 to 100 m from the horizontal wellbore and are typically less than 1 mm wide.

An EPA report (EPA, 2012b) describes 18 research projects underway to answer research questions around the hydraulic fracturing water cycle and present the progress made as of September 2012. The projects look at possible impacts of various operations on drinking water resources:

- *Water acquisition*: large volume water withdrawals from ground and surface waters;
- *Chemical mixing*: hydraulic fracturing fluid surface spills on or near well pads;
- *Well injection*: the injection and fracturing process;
- *Flowback and produced water – 'hydraulic fracturing wastewater'*: surface spills on or near well pads;
- *Wastewater treatment*: inadequate treatment of hydraulic fracturing wastewater.

The water use in hydraulic fracturing and its possible impact is summarized in Table 11.2. In Europe the experience until now has been focused on low volume hydraulic fracturing in some conventional and tight gas reservoirs, mostly in vertical wells. Hydraulic fracturing is only a small part of the EU oil and gas operations. Gandossi (2013) has reviewed hydraulic fracturing and alternative fracturing technologies.

Table 11.2 Potential drinking water issues associated with the hydraulic fracturing water cycle.

Water use in hydraulic fracturing operations	Potential drinking water issues
Water acquisition	• Water availability • Impact of water withdrawal on water quality
Chemical mixing of the fluid	• Release to surface and ground water (spills and leaks) • Chemical transportation accidents
Well injection	• Accidental release to ground and surface water (e.g. well malfunction) • Fracturing fluid migration into drinking water aquifers • Formation fluid displacement into aquifers • Mobilization of subsurface formation materials into aquifers
Flowback and produced water	• Release to surface and ground water • Leakage from onsite storage into drinking water resources • Improper pit construction, maintenance and/or closure
Wastewater treatment	• Surface and subsurface discharge into surface and ground water • Incomplete treatment of wastewater and solid residuals • Wastewater transportation accidents

Source: EPA (2012b).

So far, in 2014, the EPA study has resulted in 6 papers, where 3 relate to subsurface migration modeling and the other 3 on analytical method development (Zambrana, 2014).

11.2.5 The hydraulic fracturing fluid

The fracking fluid contains about 80% water and 20% proppant, together around 98–99.5%. Various types of proppant include silica (SiO_2) sand, resin-coated sand, and man-made ceramics. Sand containing naturally radioactive minerals is sometimes used so that the fracture trace along the wellbore can be measured. The proppant helps to keep the tiny fractures open, allowing natural gas to flow into the well. The fracking fluid flows back up the well, clearing the way for the oil and gas to be extracted.

The rest of the fracking fluid (0.5–2% by volume) is composed of a blend of chemicals, often proprietary, that enhance the fluid's properties (Clark *et al.* 2012). The concentration varies depending on the geology and other water characteristics. It may be illustrative to compare the concentration of chemicals with the most contaminated municipal wastewater that contains around 0.05% pollutants. The chemicals typically include acids to 'clean' the shale to improve gas flow, biocides to prevent organisms from growing and clogging the shale fractures, corrosion and scale inhibitors to protect the integrity of the well, gels or gums that add viscosity to the fluid and suspend the proppant, and friction reducers that enhance flow and improve the ability of the fluid to infiltrate and carry the proppant into small fractures in the shale. As producers become more water efficient, using less water per well, the relative proportion of chemicals increases.

In addition to the proprietary fracking chemicals, flowback (returning) water may also contain high concentrations of sodium, chloride, bromide, arsenic, barium and other heavy metals leached from the subsurface, as well as radionuclides that significantly exceed drinking-water standards (Soeder-Kappel, 2009). These high concentrations of inorganics are not usually successfully treated by municipal wastewater facilities and require much more expensive industrial-grade systems.

The injected fluid contains a lot of hazardous chemicals. Around 750 chemicals have been identified.

Biocides and certain petroleum products that are present in fracturing fluid are particularly hazardous chemicals that may cause health risks that range from rashes to cancer. Recent tests conducted by the University of Missouri involving testing known fracking chemicals assumed to be endocrine disruptors as well as collecting ground and surface water samples from known fracking sites yielded many telling results (Kassotis *et al.* 2014). Endocrine disruptors can interrupt hormones and glands in the body that control development, growth, reproduction and behavior in animals and humans. Among twelve tested chemicals they found that an overwhelming majority were in fact hormone disrupting and higher than average endocrine disrupting activities could be detected in water samples collected from drilling sites compared to low activities in samples taken from sites not associated with fracking activities.

The chemical composition is highly variable and consequently the toxicity of the produced water will vary a lot. The consequence of a single toxicant cannot be fully estimated until the interaction with other components in the water is taken into account. About 750 chemicals have been listed as additives for hydraulic fracturing in a report to the US Congress (Democrats

Committee, 2011). A 2010 EPA study 'discovered contaminants in drinking water including: arsenic, copper, vanadium, and adamantanes (a colorless, crystalline chemical compound with a camphor-like odor, $C_{10}H_{16}$) adjacent to drilling operations which can cause illnesses including cancer, kidney failure, anaemia and fertility problems'. In an opinion column (June, 2010) the Wall Street Journal mentioned that EPA administrator Lisa Jackson had informed Congress that there were no 'proven cases where the fracking process itself has affected water'. The Democrats Committee report reveals that 'some of the components used in the hydraulic fracturing products were common and generally harmless, such as salt and citric acid. Some were unexpected, such as instant coffee and walnut hulls. And some were extremely toxic, such as benzene and lead.' Furthermore, the report found that in the period 2005–2009 the 14 major oil companies had used hydraulic fracturing products containing 29 chemicals that are:

- known or possible human carcinogens,
- regulated under the Safe Drinking Water Act for their risks to human health, or
- listed as hazardous air pollutants under the Clean Air Act.

These 29 chemicals were components of more than 650 different products used in hydraulic fracturing. The report also found that BTEX [benzene (a 6-ring of C with one hydrogen atom to each C, C_6H_6), toluene (smell of paint thinners, one H in benzene replaced by CH_3, formula $C_6H_5(CH_3)$), ethylbenzene (smells like gasoline, formula $C_6H_5CH_2CH_3$, highly flammable), and xylenes (two H in benzene replaced by CH_3, formula $C_6H_4(CH_3)_2$)] compounds appeared in 60 of the hydraulic fracturing products. Toluene, ethylbenzene, and xylenes have harmful effects on the central nervous system. Each BTEX compound is a regulated contaminant under the Safe Drinking Water Act and a hazardous air pollutant under the Clean Air Act. Benzene also is a known human carcinogen. The oil and gas companies could not provide a complete chemical makeup for operations in 2005–2009 for the Democratic Committee. At least one chemical was decided to be proprietary or a trade secret in 279 products. In most cases the companies declared that they did not have access to proprietary information about products they purchased 'off the shelf' from chemical suppliers. In other words: the companies were injecting fluids containing chemicals that they themselves could not identify. A later report from EPA (EPA, 2012b, Table A-1) lists more than 700 identified chemicals reported to be used in hydraulic fracturing fluids between 2005 and 2011. The information was provided by 9 hydraulic fracturing service companies and 9 oil and gas operators.

11.2.6 Environmental impact of the produced water

The contaminated water from the hydraulic fracturing is called the produced water, which sounds more innocent. Both the quantity and quality of the produced water will have an environmental impact.

'Produced' water = contaminated water from fracking

Environmental concerns

Methane contamination has been a common complaint among people who live near natural gas drilling areas. A Propublica (2009) investigation (www.propublica.org) revealed that methane contamination is widespread, 'methane related to the natural gas industry has contaminated water wells in at least seven Pennsylvania counties since 2004' (see Map 2.5). Because of this contamination, several homes have blown up after gas seeped into their water supplies; there have been reports of house explosions in Pennsylvania and Ohio. In one case in 2004, a methane leak caused an explosion that killed a couple and their 17 month old grandson.

Water acquisition and consumptive use

The total volume of water required for drilling and hydraulic fracturing of a single well varies, with many factors, such as the depth of the shale formation, the horizontal extent of the wells and the geology (Clark *et al.* 2012; Nicot *et al.* 2012). The drilling operation, before any hydraulic fracturing can take place, typically requires <10% of the total water volume. Fracturing shale gas wells requires 8,700–14,400 m^3 of water per well according to EPA (2012b). New data, however, suggest that the water requirements for fracking shale gas wells might be both much larger and more variable. For example, fracking in the Marcellus region (extending throughout much of the Appalachian Basin in Eastern US and one of the largest natural gas fields in the world) requires, on average, about 17,000 m^3 per well. In the Texas' Eagle Ford Shale area fracking can use up to 49,000 m^3 of water (this corresponds to more than 2,400 truck transports á 20 m^3) per well (Cooley-Donnelly, 2012). Estimating the water requirements is further complicated by the uncertainty about how many times a single well will be fracked over the course of its productive life and limited publicly-available data. Many gas wells have a useful production life of 20–40 years, and must be re-fractured every 3–5 years in order to maintain an economically viable production flow. That indicates that the total volume of fresh water usage during the lifetime of a well is several times the volume required for one fracking operation.

Many wells are located in dry regions. For example, in the Eagle Ford Shale of West Texas rainfall is rare. Texas has been facing the worst drought in recorded history (2011), and aquifers in West Texas are dangerously low – in some cases having less than 30 days' supply of fresh water. Three years of drought, decades of overuse and now the oil industry's demands on water for fracking are running down reservoirs and underground aquifers. And climate change is making things worse. Described in another way: in 2011, Texas used a greater number of barrels of water for oil and natural gas fracking (about 632 million) than the number of barrels of oil it produced (about 441 million) according to figures from the Texas Water Development Board and the Railroad Commission of Texas, the State's oil and gas regulator (compare Table 9.7 indicating both exploration and refining). Counties in Texas with growing fracking operations, including Eagle Ford, Haynesville, and Barnett are experiencing severe drought-like conditions. In the Eagle Ford area where the entire county is experiencing drought-like conditions, 25,000 new wells are projected (Texas Water Summit Report, 2012).

Producers like to claim that the amount of water they use is small compared to that of other users, but most water used by cities, industry, agriculture, and so on, is recoverable and treatable for reuse, whereas fracking water generally cannot ever be used again except for reuse for fracking purposes. The wastewater treatment technology has not been catching up with the development of the fracking operations. A proper treatment of the produced water will lead to a considerable cost, for example using reverse osmosis technology, see Chapter 20.

> *Fracking water generally cannot ever be used again except for reuse for fracking purposes*

Fresh water is generally taken from local lakes, rivers, and streams, usually free of charge to the gas well producers, though some producers do pay local entities a low rate for some of the water they consume. The water tariffs are certainly not reflecting the true value of water. For example, in the Barnett Shale in Texas drillers paid 0.06 cents/m^3 (0.00022 cent per gallon) in 2009. Water is subsidized also to farmers, for example in water scarce areas like in California Central Valley and in the Midwest. As a result many groundwater sources have been over-extracted. A study from the Ceres Investor Network (2014) claims that fracking in the US is having a negative effect on the country's water supply in local situations (www.ceres.org/resources). According to the Texas Commission on Environmental Quality 29 communities in the State could run out of water in 90 days. Many reservoirs in Western Texas are at around 25% capacity. In Colorado, 97% of wells are in areas that are suffering water shortages. In both Texas and Colorado fracking is expected to double in the near future. Other states, including New Mexico and Wyoming, are said to be in similar situations. The Ceres report highlights a number of areas where fracking water use is equivalent to a significant fraction of residential consumption.

Some farmers and land owners have tried to make money from water by selling groundwater to the oil industry, causing aquifers to run dry. For example, a land owner in Texas earned some US$60 per truck load (compare Figure 8.2: a large tanker truck typically holds around 30 m^3. This puts the water price in the medium range of 400 US$ for 200 m^3) and could sell 20–30 truckloads every day (FracDallas, 2014). He brought in a lot of short term money, but was left with a dry well, and the land could no longer produce any food or supply the area with water. In adjacent Crockett County, fracking accounts for up to 25% of water use, according to the Groundwater Conservation District.

China has huge shale gas and oil reserves (Figure 11.2) but faces problems of water scarcity. The shale gas is found in arid regions of the country (particularly in the West) and the shale formations in China seem to require more water to frack compared to the US shales. Most of the shale gas is found in mountainous regions that are prone to earthquakes and at great depth. The Sichuan province is considered to have the greatest potential for shale gas, though the state's water pollution issues are already significant.

Mexico suffered a severe drought in 2012 and does not seem to have sufficient water supplies to expand the fracking efforts. South East England, an area the fracking industry is particularly interested in, already has water supply problems and was in drought recently. Both Mexico and UK have suffered extreme weather with both droughts and floods (see Chapter 4.2). Water scarcity is also a critical issue in South Africa. For example, large shale gas deposits have been found in the Karoo semi-desert – and have led to much opposition by environmental groups (e.g. WWF-SA).

Development of new fluids

Halliburton has announced (March 2013) a new technology – marked as CleanStream and Clean Wave – that it claims will allow hydraulic fracturing drillers to utilise saline, brackish or other non-potable waters for their fracking operations, without the need for treatment. The new application, called H_2O Forward, combines existing company technologies to improve the chemistry of the fluid and reduce the volume of fresh water needed to unlock oil and gas in shale formations (www.halliburton.com).

eCORP Stimulation Technologies (www.ecorpstim.com) has developed a process (2013) that extracts unconventional hydrocarbons without the use of water or chemical additives, using liquid propane. The company states that the environmental impact of shale exploration is considerably reduced. A fluorinated form of propane is used to suppress its flammability. Another waterless process replaces water with nitrogen, an option employed by the company Air Products. However, nitrogen is only really practical in an ideal situation which is in shallower wells that can stay propped up without the use of proppants like sand as nitrogen is a poor proppant carrier (www.airproducts.com/industries/Energy/OilGas-Production).

Groundwater contamination

A lot of attention has been directed toward the possibility of subsurface migration of fracturing fluids or hydrocarbons into groundwater aquifers (Zambrana, 2014). Low-permeability natural gas resources are in geologic formations located at depths of 450–4500 m below the surface, with natural gas wells averaging 2000 m (Clark *et al.* 2012). At these depths, the formations may underlie drinking water aquifers, which are commonly 30–100 m below the surface. However, there are various risks related to the handling of the fracking fluid related to

- leakages from the drilling;
- handling of returned water – spills and accidents.

Several different pathways for migration have been proposed but the risks vary according to the National Energy Technology Laboratory (NETL, 2013). The fracking wells pass through aquifers. One potential pathway is through the casing/wellbore annulus when there is poorly cemented casing across and beneath potable water aquifers (Vengosh *et al.* 2013). In this situation, the drilling of new shale wells could connect deeper natural gas-bearing formations with shallower aquifers and in the presence of sufficient pressure differential, cause natural gas to reach the water zone. Another potential pathway is a case where the drilling of the shallow section of a new shale gas well temporarily permits communication between shallow gas-bearing zones and water supply aquifers. Pressure fluctuations under these circumstances could potentially cause gas communication. Also, poorly cemented wellbores from long abandoned ‘orphan’ wells can create a pathway. Several recent studies have attempted to find incontrovertible positive evidence of a connection between hydraulic fracturing and shallow water zone contamination, without success. A number of ongoing studies are continuing to assess this risk (NETL, 2013).

There is a recognized problem to bring up the produced water safely. There may be cracks in the casing, and trucks may spill water. The risks are not always fully understood and the enforcements of the regulations are not always obvious (Gruver, 2011). There have been several mishaps of hydraulic fracturing influencing the groundwater aquifers, sometimes due to negligence. Flowback water, in addition to fracking chemicals, can also contain brine, heavy metals and radioactive contaminants in addition to the methane that is released.

It is with the often-expensive handling of this flowback that many people are concerned. If properly treated, returned water can be reused in other fracking operations. Still, treatment methods for the produced water are usually inadequate to achieve any drinking water standard. As long as there is not a transparent and strongly regulated operation it is difficult to minimize or remove all the risks.

A study at Duke University, North Carolina, USA has found that much of the naturally occurring radioactivity in fracking wastewater might be removed by blending it with another wastewater from acid mine drainage. Laboratory tests so far have confirmed that blending the two toxic components in the right proportions some of the fracking contaminants can be bound in solids that can be removed before the water is discharged (http://nicholas.duke.edu/news/acid-mine-drainage-reduces-radioactivity-fracking-waste).

The leakage potential is also of serious concern because water supplies can be contaminated by exposure to methane. The leakage can arise in several ways – leakage to the surface through natural underground fractures outside of the wellbore, leakage through poorly constructed well casings and the cement barriers around the casings, and leakage at the surface from leaky infrastructure and pipelines. A Duke University study (Osborn *et al.* 2011) found that methane levels in private water wells are, on average, 17 times higher in wells that are within 1 km of a natural gas drilling site. When the researchers fingerprinted the methane itself, the chemical signatures of the gases matched the gas from the gas wells. The Duke University research team found new evidence in 2013 that links hydraulic fracturing for natural gas to elevated methane levels in private water supplies across Northeastern Pennsylvania (Jackson *et al.* 2013). Methane was detected in 115 of 141 drinking water wells sampled. Wells within 1 km of a natural gas operation showed a 6-fold increase in average concentration of methane. Wells close to gas drilling also showed much higher concentrations of ethane and propane that are signatures of fracking.

Another category of risk is potential accidents. Spillage of fracking fluids or wastewater during routine operations or during storms can jeopardize nearby surface and ground water supplies. Another risk, well known in the oil and gas industries, is blowout of a well and subsequent fire, as is reported to have occurred recently in Jiaoshizhen, China (New York Times 11 April 2014).

A well in the Marcellus shale formation generates on average 5200 m^3 of wastewater (12% drilling fluids, 32% flowback; 55% brine). Typically the salinity in the Marcellus brine is around 250 g/L, 10 times seawater (Lutz *et al.* 2013). Of the water that goes down the well bore as a medium for the fracking a significant fraction of the injected fluid comes back out of the wells as wastewater (including drilling muds, flowback water and produced water that is released from underground sources). The volume of produced water that is returned varies greatly, depending on the geological characteristics of the formation; it can be as low as 15% and as high as 300% of the injected volume.

The flowback water that does come back up is stored in tanks or often in lined or unlined above-ground pits until it can be pumped into tanker trucks and hauled off for deep well injection far below the earth's surface. Some of the flowback water spills onto the ground around well pads where it contaminates the local area and possibly produces adverse health effects for rig workers and neighboring community. Many cases have been documented where tankers leaked, where valves were accidentally or intentionally opened allowing the produced water to flow out onto roadways and roadsides, where traffic accidents resulted in massive spills, or where that water was illegally dumped onto private or public land or into rivers, lakes or streams rather than being pumped into injection wells, as claimed by drilling operators.

Most of the water used for fracking should be considered permanently lost water. Flowback water and produced water will be unavailable for further use. The technology to clean it up is not fully developed and the treatment will be expensive. According to Endress + Hauser, Inc. the cost of cleaning produced water is 300 times greater than municipal waste water and 3,000 times greater than irrigation water (Endress + Hauser, 2014).

Threats to surface waters

The development of any gas well creates surface disturbances as a result of land clearing, infrastructure development and release of contaminants produced from the drilling and fracturing operations. Contamination from flacking-fluid chemicals adds extra threats. Reductions in water levels, contamination of streams from accidental spills, and inadequate treatment practices are realistic threats. More scientific measurements and documentation are needed that will inform decision making and ensure protection of water resources.

Gas wells are often sited close to streams, increasing the probability of harm to surface waters. Entrekin *et al.* (2011) have used geographic information system (GIS) tools to generate detailed drainage-area networks in shale reservoirs where gas wells occur at high densities. As the densities increase, the proximity of wells to stream channels may also increase. This may result in a greater risk of water reduction as a result of pumping as well as contamination from leaks and spills from the fracking operations. Onsite waste ponds could overflow, spill or leach into groundwater and into streams close to the site. The wastewater contains high concentrations of total dissolved solids (TDS), from around 5,000 to more than 100,000 mg /L. Common municipal treatment plants are either unable to treat this water, or have to limit their intake of recovered wastewater from the fracking operations.

Hydraulic fracturing fluids are believed to be the cause of the widespread death or distress of aquatic species in Kentucky's Acorn Fork, after spilling from nearby natural gas well sites in 2007, according to a joint study by the US Geological Survey and the US Fish and Wildlife Service (Papoulias-Velasco, 2013). The Acorn Fork, a small Appalachian creek, is designated by Kentucky as an Outstanding State Resource Waters. In the study it was found that the hydraulic fracturing chemicals that leaked from surface pits caused a sharp, sudden rise in acidity (the pH dropped from 7.5 to 5.6), and content of dissolved elements including iron and aluminum (the stream conductivity increased from 200 to 35,000 microsiemens/cm) killed off or harmed local fish populations along a 2 km stretch of the creek. The study is thought to be the first on the effect of fracking fluids on aquatic creatures.

Air quality

Any oil and gas drilling operation impacts air quality. Dust and engine exhaust from truck traffic and emissions from diesel-powered pumps are health hazards. These emissions include primarily ozone precursors like NOx and non-methane volatile organic compounds (VOC), and particulates. In some cases extremely high ozone levels have been reported, comparable to major cities in their worst conditions (Gruver, 2011).

Air quality is also influenced by methane emissions during the well completion process when wells are flowed back or tested. When the fracking fluid reaches the surface it also contains some gas and air pollutants, such as benzene that may escape into the atmosphere.

Emissions can include emissions from flares (see 11.6). Still another source of air pollution is non-combustion particulates, both from gravel roads constructed for drill pad access as well as from silica dust from proppant handling during hydraulic fracturing. The silica sand can lodge in lungs and cause silicosis.

Equipment during the gas and liquids production process create emissions, including inadvertent methane releases from valves, compressor blowdown, and VOCs such as BTEX that escape from condensate or oil tanks. Several studies are under way (NETL, 2013) to attempt to quantify the individual as well as cumulative impacts.

The treatment sometimes has dangerous consequences. A pond with the contaminated fluid can be treated with big mixers or injectors that create a mist of small water drops. In a warm climate the drops easily evaporate and the contaminated water is transformed into polluted air. Naturally this air will influence the environment and potential drinking water wells. Many particulates and chemicals can be released into the atmosphere, such as sulfuric dioxide (SO_2), nitrous oxide (N_2O), VOCs, benzene, toluene, diesel fuel, hydrogen sulfide (H_2S). This can have serious health implications.

Triggering of damaging earthquakes

In a lot of locations it has been recorded that high-volume fracking generates numerous small earthquakes, and the possibility of a large earthquake cannot be ruled out (Turcotte *et al.* 2014). However, the largest earthquake attributed to high-volume fracking had a magnitude of 3.6, which is too small to do surface damage. On the other hand, some larger earthquakes, including a magnitude-5.7 quake that struck Oklahoma in 2011, have been attributed to wastewater injection (Ellsworth, 2014).

11.2.7 Making fracking transparent

Water quantity and quality impacts must be fully reported, monitored, and regulated. Shale gas and fracking come with severe risks especially if not managed through strongly regulated processes with clear ‘rules of engagement’ and penalty systems if these are not enacted. Science needs to catch up in order to support said development of regulations and to safeguard the environment and humans from negative impacts. Resources need to be invested in science – such as treatment technology to clean produced water – not least by nations waiting to capitalize on shale gas as an energy resource.

Publicity and regulations

Environmental concerns are having a major impact on public opinion. A poll by the Pew Research Center (US) in the Fall of 2013 found that 49% of those surveyed opposed the increased use of hydraulic fracturing, while 44% supported it. In 2010, New York, one of four states sitting atop an estimated 4×10^{12} m^3 (141 trillion cubic feet, Tcf; compare Figure 11.2) of recoverable natural gas in the Marcellus Shale formation, became the first state to impose a moratorium on hydraulic fracturing (New York Times 30 April 2014). In February 2014 Colorado became the first state to directly regulate methane emissions from oil and gas operations. The shale gas boom has led to a vigorous debate about fracking in the US and in a few other countries where fracking is just getting underway or is contemplated.

Fracking is today a poorly regulated industry in the US. Hydraulic fracturing is now regulated by the states, with no significant federal oversight. Some big oil- and gas-producing states require some disclosure about the mix of chemicals and fluids used to frack thousands of wells across the country. In June 2014 Washington Post reported that 4 in 10 new oil and gas wells near national forests and fragile watersheds or otherwise identified as higher pollution risks escape federal inspection. The agency struggles to keep pace with the drilling boom. The shale gas industry is exempt from seven major federal regulations, including the Clean Water Act, the Safe Drinking Water Act, and the Superfund Law which requires that polluters remediate for carcinogens like benzene, except if they come from oil and gas production. The Resource Conservation and Recovery Act also exempts fracking from regulations pertaining to hazardous waste.

In June 2008, 303 m^3 of hydrofracturing fluid from a natural gas well were applied to a 0.2 ha area of mixed hardwood forest on the Fernow Experimental Forest, West Virginia, USA (Adams, 2011). During application, severe damage and mortality of ground vegetation was observed, followed about 10 days later by premature leaf drop by the overstory trees. Two years after fluid application, 56% of the trees within the fluid application area were dead.

The shale gas industry in the US is exempt from seven major federal regulations

Corporations are exempt from revealing the chemicals used in fracking fluid, the so-called Halliburton Loophole, although some voluntary disclosure is now taking place. The Clean Water Act was made a law in 1974. This was of major interest since the Americans get half of their fresh drinking water from underground sources. The USEPA completed a study in 2004, finding that fracturing 'poses little or no threat' to drinking water (EPA, 2012a). The EPA also concluded that no further study of hydraulic fracturing was necessary. The 2004 EPA study has been called 'scientifically unsound' by EPA whistle-blower Weston Wilson. In an October 2004 letter to Colorado's congressional delegation, Wilson recommended that EPA continue investigating hydraulic fracturing and form a new peer review panel that would be less heavily weighted with members of the regulated industry (Wilson, 2011). In March of 2005, EPA Inspector General Nikki Tinsley found enough evidence of potential mishandling of the EPA hydraulic fracturing study to justify a review of Wilson's complaints.

In 2005 the oil and gas industry was granted an exemption from the Federal Safe Drinking Water Act (SDWA), making oil and gas the only industry allowed to inject toxic fluids – unchecked – directly into good quality groundwater without oversight by the USEPA. This exemption from the SDWA has become known as the 'Halliburton loophole' because it is widely perceived to have come about as a result of the efforts of Vice President Dick Cheney's Energy Task Force. Before taking office, Cheney was CEO of Halliburton, which patented hydraulic fracturing in the 1940s, and remains one of the three largest manufacturers of fracturing fluids. Halliburton staffs were actively involved in the review of the 2004 EPA report on hydraulic fracturing. At a seminar for the Society of Petroleum Engineers Veatch (2008) presented the development of fracking: 'hydraulic fracking was born in Hugoton Field, Kansas in 1947. … Since then it has turned the world green with money.' He also cites A. B. Waters from Halliburton in 1980: 'Hydraulic fracturing has generated more profit for the petroleum industry than any other process except for exploratory and development drilling.'

At the state level most oil and gas agencies do not require companies to report the volumes or names of chemicals being injected during hydraulic fracturing. Thus, neither the Government nor the public can evaluate the risks posed by injecting these fluids underground.

The environmental price will be high and still the polluters are quite protected. According to Water 21 Global News Digest (22 November, 2011) state regulators told a congress committee in November that fracking should be overseen by states and not central Government. Republican Bob Gibbs told the meeting: 'We must be sure that the EPA thinks carefully before developing new Clean Water Act standards that would needlessly restrict this important industry and burden it with an additional layer of duplicative federal regulations.' As mentioned, some signs of hope can be seen, for example in Colorado and New York. In April 2012 the EPA (EPA, 2012b) issued a set of regulations for the oil and natural gas industries, but under the Clean Air Act (only addressing emissions, leaks and spills) and not the Safe Drinking Water Act (pumping chemicals underground). Even George P. Mitchell, the Texas wildcatter who pioneered the use of fracking, has called for more transparency and tighter regulation. In the absence of well-defined federal oversight in the US states are starting to assert control. In 2011 the North Dakota (where the huge Bakken shale formation is located) legislature passed a bill that said, in effect, fracking is safe, end of discussion.

We can't manage what we don't measure.

In April 2014, Baker Hughes, one of the largest US oil service companies, said it plans to disclose all chemical ingredients contained in its fracking fluids, without giving specific formulas (Washington Post, 10 May 2014). More legislation on fracking have been passed or discussed recently:

- *Massachusetts 2013*: The Massachusetts joint committee on Environment and Natural Resources has approved a bill intended to create a ten-year moratorium on hydrofracking in the state.
- *California 2013*: The California State Government released proposed rules for fracking that will require companies using the procedure to obtain state permits, test groundwater quality and notify neighboring properties before beginning work.
- *California 2014*: The California Division of Oil, Gas and Geothermal Resources has announced that it is to review the state's underground injection control program, two weeks after it ordered seven independent oil companies to stop wastewater injection work at 11 disposal wells for fear they might be contaminating drinking water sources in the local county. The Department is reviewing the program in conjunction with the US EPA to ensure it complies with the Safe Drinking Water Act.
- *UK 2014*: During the House of Lords committee stage of the Water Bill, Lord Whitty urged inclusion of a clause that would amend the environmental permitting regime to include a condition whereby companies intending to engage in fracking would have to show from the outset that they had the funds to meet cleanup costs, in the event that pollution to groundwater, aquifers or water supplies should occur. Responding for the Government, Lord de Mauley announced that the Department of Energy and Climate Change and the shale gas industry are working to put in place a scheme to cover liabilities even if an operator is no longer in business.

  A study led by Durham University has warned that the lack of publicly-available data on the UK's onshore oil and gas drilling means there are significant 'unknowns' about the safety of future fracking wells.
- *European Union 2014*: The European Commission has adopted a recommendation aiming to ensure that proper environmental and climate safeguards are in place for fracking. The document suggests member states should carefully assess environmental impacts and risks, ensure that the integrity of the well is up to best practice standards, and check the quality of local water, air and soil before operations begin, to monitor any changes and deal with emerging risks. The European Economic and Social Committee, EESC (www.eesc.europa.eu) thinks that the current framework on 'exploration and production of hydrocarbons', if correctly implemented, is sufficient for use at local community level. The committee does not see any need to adopt a specific 'shale gas directive', at least for the time being.
- *The European science and technology network on unconventional hydrocarbon extraction* was launched mid-July 2014 (https://ec.europa.eu/jrc/uh-network). The network aims to

bring together practitioners from industry, research, academia and civil society, so as to ensure a fair and balanced exchange of ideas. The network will structure the dialogue among the stakeholders, fostering open information and knowledge sharing. Research activities and results will be presented and discussed and gaps in R&D needs will be identified. It will examine knowledge gained from exploration and demonstration projects and identify and assess emerging technologies including their economic, environment and climate impacts.

- *Canada 2013*: Disclosure of fracturing fluid additives is mandatory in British Columbia and Alberta and can be found online (Frac Focus, 2013). New Brunswick Government is also requiring mandatory disclosure.
- *Germany 2014*: Germany has drafted a law that would largely ban fracking – the country's legislature will discuss this after the summer break, the country's press report. The ban will apply to any activity at depths of less than 3000 m. Testing of technology will be allowed provided the fracking fluids do not endanger groundwater. The law will apply till 2021, at which point it will be reviewed.
- *New Zealand 2014*: The NZ Government has issued best practice guidelines for fracking, which warn that fracking fluids can migrate into drinking water and must be controlled.
- *China*: In China shale gas is at quite a rudimentary stage. Production is still low and no real breakthrough is predicted in the near future. Probably, shale gas will not start to play a significant role in China before 2030. The technology that is being used in the US doesn't seem to be the most appropriate one for China. The shale gas is located deeper than in the US and the water scarcity in these regions in China is serious. Therefore the current cost of drilling a shale gas well in China is reported to be several times higher than that of a typical shale gas well in the US. Still, the prediction is that from 2030 on the shale gas production will quickly pick up and grow fast. For the moment China's major national oil firms appear to be reluctant to make large R&D investments in domestic shale gas because of the alternative investment choices currently available to them.

In April 2010 the state of Pennsylvania banned Houston-based Cabot Oil & Gas Corp. from further drilling in the entire state until it plugs wells that are believed to be the source of contamination of the drinking water of 14 homes in Dimock Township, Pennsylvania. The investigation was initiated after a water well exploded on New Year's Day in 2009. The state investigation revealed that Cabot Oil & Gas Company 'had allowed combustible gas to escape into the region's groundwater supplies.' Dimock is now known as the town where residents' water started turning brown and making them and their animals sick after shale gas fracking was initiated under their land in the late 1990s (underground property rights in PA do not vest with surface property rights). Dimock and other communities in the Delaware River basin are located above the Marcellus Shale Deposit.

Another Pennsylvania story involves the Hallowich family in Washington County. Quoting from the story (2013): 'When drilling company Range Resources offered the Hallowich family a US$ 750,000 settlement to relocate from their fracking-polluted home in Washington County, Pennsylvania, it came with a common restriction. Chris and Stephanie Hallowich would be forbidden from ever speaking about fracking or the Marcellus Shale. But one element of the gag order was all new. The Hallowichs' two young children, ages 7 and 10, would be subject to the same restrictions, banned from speaking about their family's experience for the rest of their lives'. The Hallowich family's gag order is only the most extreme example of a tactic that critics say effectively silences anyone hurt by fracking. It's a choice between receiving compensation for damage done to one's health and property, and publicizing the abuses that caused the harm. Virtually no one can forgo compensation, so their stories go untold.

Stories of Pennsylvania communities like Dimock and others in Colorado, Wyoming, Utah, and Texas that claim to have been impacted adversely by fracking were popularized in an American documentary film released in 2012 entitled 'Gasland'. It was followed up by 'Gasland 2' after its conclusions were questioned strongly and even denied by the US oil and gas industry (Regina Hopper: Frack-no-Phobia. America's Natural Gas Alliance, http://anga.us/blog/2012/7/27/frack-no-phobia, 27 July 2012). Federal and State investigations are underway.

The mineral rights are different in the US than in many other countries. The US legal system gives individuals ownership of mineral rights under their land. Consequently the owner can lease the rights to others. That has accelerated drilling in comparison with other nations, where the mineral rights are controlled by governments. Moreover, many of the richer shale gas areas in the US have a small population. There is also another consequence of the ownership, for example in Texas: property owners have no control over the extraction of the oil that lies beneath their land, unless they also own mineral rights.

The intense environmental debate over fracking in the US has seemingly been observed by European nations inducing different responses among its governments (KPMG, 2012). Though effective environmental lobbies and environmental laws have played their part in slowing growth, also technical (mainly due to different characteristics of explored shale formations in Europe compared to the US) and administrative issues have been listed as reasons for this. Consequently it can be argued that Europe is unlikely to experience a shale gas revolution at the scale that has been observed in the US.

The economic driving forces to extract oil and gas using hydraulic fracturing are certainly huge (Zuckerman, 2013). Therefore its use will probably continue to expand for a long while. Still there are doubters have been making themselves heard too. Some pessimists worry about the speed at which shale-bed wells run dry (The Economist, Nov 16, 2013). However, we need to emphasize that shale oil and gas are not renewable sources of energy. Getting the shale gas will buy some time but renewable energy sources have to be developed and ultimately we need to make a transit to them.

11.3 OIL ACCIDENTS – NORTH AMERICA

> *We learn geology the morning after the earthquake.*
> Ralph Waldo Emerson, The Conduct of Life, 1860.

Ocean pollution from oil is primarily noted by the public when an oil well at sea is damaged or when an oil-carrying ship leaks large amounts of oil into the sea as a result of an accident. Despite this perception,

> most oil pollution in the ocean actually comes from municipal and industrial runoff, cleaning of ship's tanks and other 'routine' events.

Spills are commonplace in the oil industry and are a serious problem in particular in a developing nation. The fault can be said to lie in no small part within ourselves and our appetite for oil. On the other hand the high potential profits are a great driver to take high risks for the industry.

11.3.1 Mexican Gulf 1979 and 2010

Two major oil disasters in the Gulf of Mexico have had a major impact on water quality, one in 1979 and the other in 2010. Many of the causes for the spills are the same: oil companies trying to cut corners for short term economic gains.

In 1979 a huge oil spill occurred in the Mexican Gulf. The Ixtoc I platform, just west of the Yucatan Peninsula, was operated by Pemex (Petróleos Mexicanos). At the time of the accident Sedco 135F was drilling at a depth of about 3600 m below the seafloor. The exploratory oil well blew out, spilling an estimated 500,000 m^3 (3 million barrels) of crude oil into the open sea.

On 20 April, 2010 the world was informed about another huge leak in the Mexican Gulf. An explosive blowout of the well had turned the US$ 560 million Deepwater Horizon drill rig into a pile of charred and twisted metal at the bottom of the sea and 11 workers had died in the explosion. The oil spill caused enormous damage not only in the marine life of the Mexican Gulf but also in the wetlands and water supplies along the coasts around the Mexican Gulf. Only weeks before the explosion, on 2 April, President Obama had announced plans to allow drilling off the East Coast. No big oil spill had taken place in more than 20 years. The President declared that ‘it turns out that oil rigs today generally don’t cause spills.’ The New York Times reported (May 13, 2010) that over 300 offshore drilling permits had been issued by the US Government without proper approval by US National Oceanic and Atmospheric Administration (NOAA) already in 2009.

A ‘blowout’ on an oil platform occurs when a mixture of pressurized natural gas, oil, mud, and water escapes from a well, shoots up the drill pipe to the surface, expands and ignites. Wells are equipped with structures called blowout preventers, BOP. A BOP is a massive five story, 450 ton stack of shut-off valves, rams, housings, tanks and hydraulic tubing that sits on top of the well is supposed to shut off the flow, but somehow the blowout preventer failed. Two switches – one manual and an automatic backup – failed to start it.

The demand for oil is so great that ever greater risks are taken to explore the oil under the deep sea. Shrinking reserves, rising oil prices and spectacular offshore discoveries have ignited a global rush into deep water, not only in the Mexican Gulf but also for example outside Brazil and Angola. The drilling technology has seen a tremendous development and it is now possible to drill more than 10,000 m down through water and rock. However, the methods for preventing blowouts and cleaning up spills have not kept pace. The economics is enormous. By 20 April the Deepwater Horizon was six weeks behind schedule and US$ 58 million over budget due to problems in the drilling of the well, according to documents from MMS (Minerals Management Service). Every day of delay would cost BP around half a million US$ so BP had chosen to drill the ‘fastest possible way’.

Safety plans and risk analysis

The commercial greed and ruthlessness is reflected in the drilling plan, rubber stamped by MMS. The Draft Environmental Impact Statement (DEIS) for a cluster oil and gas lease sales that included the site of the Deepwater Horizon rig, was seriously flawed. Prepared by the MMS the DEIS never assessed the impact of a catastrophic spill, limiting its focus to spills less than about 700 m^3. In a spill response plan for the whole Gulf, BP claimed that it could recover nearly 80,000 m^3 (500,000 barrels) a day using only standard technology. Even a worst case spill would do minimal harm to the Gulf's fisheries and wildlife – including walruses, sea otters and sea lions. There are no walruses, sea otters or sea lions in the Gulf! The blunders had appeared in other oil companies' spill-response plans as well. They had simply been cut and pasted from older plans prepared for the Arctic. BP had also listed as an emergency responder a marine biologist who had been dead for years.

During the Bush Administration in 2004, the MMS granted a 'categorical exclusion' from the National Environmental Policy Act (NEPA) to certain oil and gas activities in the Gulf of Mexico, including individual exploration plans. The MMS essentially said that it would not thoroughly review the environmental impacts of certain activities, including such activities as the exploration phase for the Deepwater Horizon site, *unless* it would, for example, take place in relatively untested deep water or utilizing new or unusual technology. The *Deepwater Horizon* project was deep and it used new technology (Cleveland, 2013).

In the wake of the Deepwater Horizon accident, the MMS was heavily criticized for alleged conflicts of interest among its competing missions. MMS had the task to collect royalties from oil and gas produced on federal lands and issuing energy leases; at the same time it was also responsible for policing offshore drilling and setting regulations for the industry. President Barack Obama noted after the accident that there was a 'cozy relationship' between federal regulators at the MMS and the industry they police. As a direct result of the Deepwater Horizon events the MMS was broken up into three separate bureaus.

BP had claimed to develop strict safety procedures, in particular after a terrible explosion in 2005 in a Texas City refinery, when 15 people were killed and another 180 were injured. The accident in 2005 resulted in financial losses exceeding US$1.5 billion. According to the US Chemical Safety Board, the Texas City disaster was caused by 'organizational and safety deficiencies at all levels of the BP Corporation'. Warning signs of a possible disaster were present for several years, but company officials did not intervene effectively to prevent it.

In March 2006 there had been a leakage on the Alaska North Slope from corroding pipelines from BP's Prudhoe Bay operation. More than 750 m^3 (200,000 gallons) of crude oil was spread over the tundra and a nearby frozen lake. This was the largest spill ever to occur on the North Slope. As part of the guilty plea BPXA (British Petroleum Exploration Alaska, Inc.) agreed to a total of US$20 million of which US$12 million was criminal fine, and another $4 million was criminal restitution to the State of Alaska. BP also served a three-year term of probation.

Apparently, the safety instructions did not address the most relevant challenges. For example (according to CNN Money, 24 January 2011) BP had strict guidelines barring employees from carrying a cup of coffee without a lid – but no standard procedure for how to conduct a 'negative-pressure test', a critical last step in avoiding a well blowout. Such a test might have saved the Deepwater Horizon. There is always a tension between safety, which costs a lot, and short term profit. The costs for the spills are astronomical. The Presidential Commission examining the accident noted: 'The Macondo well blowout can be traced to a series of identifiable mistakes made by BP, Halliburton (BP's cementing services provider), and Transocean (that owned the platform) that reveal such systematic failures in risk management that they place in doubt the safety culture of the entire industry.'

Risk analysis and safety culture have to be taken seriously by the oil industry.

The impression is that business as usual continued after Deepwater Horizon. In March 2011, the Federal Government awarded Shell Offshore Inc. the first new deep-water oil exploration plan approved since the Deepwater Horizon explosion. The Federal off-shore drilling regulator, Bureau of Ocean Energy Management, Regulation and Enforcement, BOEMRE (replacing MMS), approved Shell's plan after concluding that 'an accidental spill event is not very likely to occur.' The Federal agency had based its analysis on a 1-in-4000 chance oil spill risk scenario even though industry documents had shown the chance of a major spill at 1-in-43 (Environment News, 2011). Environmental groups claimed the Government's risk calculations were flawed and Shell's drilling plan was not sufficient to protect communities from another major oil spill in the Gulf. For example, the plan had not taken into account the weaknesses of blowout preventer technology in the deep sea environment. During hearings by the National Commission on the Deepwater Horizon events numerous experts admitted that the preventer technology had not been adequately tested for harsh deep-water conditions. Again, it looks like the familiar competition between economy, risk and environment.

The number of drilling permits issued in the US Gulf reached a record 807 in September 2013 (Bloomberg Businessweek, Oct 3, 2013), an increase of more than 14% over the same period in 2012. According to oil-services company Baker Hughes there were 62 rigs operating in the Gulf in September 2013, more than at any time in 4 years. In August 2014 BP has rebuilt its armada of deep-water drilling rigs in the Gulf to nearly double its size compared to April, 2010 (Business News, 21 April 2014).

Four years after the Deepwater Horizon we note that the US Government is pushing for more drilling in difficult and sensitive terrain, for example in the US Arctic Ocean. There the conditions are so rough that Shell's test-drilling platform literally ran aground during an average winter storm (see 11.5).

Immediate environmental consequences

According to calculations made by the US Government some 780,000 m^3 (4.9 million barrels) were spilled in the Mexican Gulf between 20 April and 15 July, 2010. 80 km offshore and more than 1500 m deep underwater on the seafloor BP's Macondo well was spewing oil for almost three months. The first estimates in April were 160 m^3/day (1,000 barrels/day). These estimates were upgraded week by week. Before the leaks were capped the estimates had been upgraded to around 9500 m^3/day (60,000 barrels/day). This corresponds to something like an Exxon Valdez (see below) every 4–5 days (more details in Wikipedia; Bourne, 2010; Cleveland, 2013).

Around 780,000 m^3 of oil were spilled in the Mexican Gulf in 2010.

The US Government has estimated that BP had removed about a quarter of the oil. Another quarter had evaporated and the lighter and intermediate components have dissolved. Solar radiation will intensify the evaporation. A third quarter had been dispersed in the water as small droplets, which might still be toxic to some organisms. Wave action will mix the remaining oil with water to create an emulsion, called mousse that is about 80% water. By the time this mixes with debris and is so heavy that pumps can only raise it less than one meter. The last quarter – still about five times the amount released by Exxon Valdez – remained as slicks or sheens on the water or tar balls on the beaches.

The official estimates of the amount of oil flowing into and later remaining in the Gulf have been the source of significant controversy. The initial estimate of the oil flow and the subsequent estimate of the remaining oil at the end of the summer of 2010 were unrealistically low. This created the impression that the Government as well as BP were either not fully competent to handle the spill or not fully candid with the public about the scope of the problem (Cleveland, 2013).

BP was forced to set aside a fund of US$ 20 billion to compensate for the damage caused by the oil spill. In January 2011 the White House oil spill commission released its final report on the Deepwater Horizon accident. BP, Halliburton, and Transocean were all, in different ways, responsible for the accident. In the report they are all blamed for making a series of cost-cutting decisions and the lack of a system to ensure well safety. The report also concluded that ‘the root causes are systemic and, absent significant reform in both industry practices and Government policies, might well recur’. As of February 2013, criminal and civil settlements and payments to a trust fund had cost BP US$ 42.2 billion.

Long term environmental consequences

The question appears how long the impact of a spill can last. This has been studied for more than ten years after the Ixtoc spill. In a protected reef lagoon the Ixtoc tar mat was still partially buried in the sediments. On the ocean side of the reef, where winds and waves and currents are stronger, no oil remained. Where there is wave energy and oxygen, sunlight and microorganisms will degrade the oil. The bacteria feed on oil and methane and will deplete the water of oxygen. Since water in the deep sea mix very slowly oxygen depleted zones could persist for decades. When oil falls to the bottom and gets entrained in low-oxygen sediments, as in a lagoon or in a march, it can hang around for decades, degrading the environment. Naturally this will have a catastrophic consequence for fishing.

Another impact of the spill is the heavy use of the dispersant Corexit 9500. BP has claimed that the chemical is no more toxic than dishwashing liquid. However, it was used on the 1978 Amoco Cadiz spill outside Brittany, France, when 223,000 tons were lost and it was found that it was more toxic to marine life than the oil itself.

In the Mexican Gulf almost 60 tons of subsea dispersants (Corexit) had been used until early May 2010. On May 19, 2010, the EPA informed BP that the company had to immediately identify and use less-toxic forms of chemical dispersants. Scientists were concerned that the unprecedented use of chemical dispersants could pose a significant threat to the marine life. Using subsea dispersants could contribute to the formation of underwater oil plumes by shaping the oil into smaller droplets (Cleveland, 2013). On May 20, 2010, the EPA began to post data from BP on the company’s monitoring and sampling programs at the EPA web site. On the same day BP told the EPA that it could not find a safe, effective and available dispersant to use instead of Corexit. Some of the ‘alternative’ chemical ingredients were kept secret because of confidential business information. On May 27, 2010, a scientific conference on dispersants was held, organized by the Coastal Response Research Center at the University of New Hampshire, NOAA, EPA and the US Coast Guard. The conclusion was that until then the effects of dispersing oil into the water column had generally been less environmentally harmful than allowing the oil to migrate on the surface into the sensitive wetlands and near shore coastal habitats. The issue remains: what is less harmful at one place may be much more harmful at another one.

The negative effects of oil on organisms and ecosystems are well-documented. The area affected by the Deepwater Horizon oil spill has some of the world’s most productive marine and coastal ecosystems. Oil causes harm to wildlife through physical contact, ingestion, inhalation and absorption. Long term damage to lower trophic levels is difficult to assess, but could pose ecological risks for years, based upon interference with metabolic functions of thousands of species; benthic organisms in the inner and outer continental shelves could be affected from oil coating of substantial portions of the ocean floor.

In April 2011, one year from the onset of the Deepwater Horizon spill, dead dolphins were found along the Gulf Coast. They had oil in the bodies. Fifteen of the 406 dolphins that had been washed ashore in 14 months had oil on their bodies; the oil found on eight of them was linked to the Deepwater Horizon oil spill. In May 2010 scientists at the National Institute for Undersea Science and Technology (NIUST) discovered large oil plumes in the deep waters of the Gulf of Mexico, including one as large as 16 * 5 km wide and 100 m deep at depths of 1,000–1,400 m (Cleveland, 2013). Initial reports suggested that the plumes are depleting the oxygen dissolved in the water column, which could pose a threat to marine life forms at varying trophic levels. Later, several other locations of plumes have been found. Furthermore, oil was found in the sediments of the DeSoto Canyon, a fissure that leads from the Deepwater Horizon site to just 60 km from Panama City Beach in Florida. Chemical 'fingerprinting' confirmed that the oil from the plumes and the sediments was from the BP oil spill source.

From the origin of the leak, to the amount of oil released into the environment, to the spill's duration, the 2010 Gulf of Mexico oil spill poses unique challenges to human health. A first report on early signs of biological damage from the Deepwater Horizon oil spill has been reported in September 2011 (International Herald Tribune, 28 September 2011). A minnowlike fish that is a major source of food in wetland marshes along the Gulf of Mexico has been examined. Tests of the fish showed cellular changes like poorly regulated estrogen, potentially signalling an impact on reproduction. Other cellular changes could point to impaired biological performance and health.

Four year later, the disaster still is not over. Acute impacts could be seen – things like oiled birds and marine mammals, ecosystems that were altered. There are also chronic consequences where we might not see an immediate effect. These chronic effects are tricky because they require monitoring over a long period of time. A group of 14 research institutions are working in a program called Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG, see www.gulfbase.org/project) to monitor the long-term effects and mechanisms of ecosystem recovery from the Deepwater Horizon blowout. The long term effects are still unknown but after more than 3 years the groups have found:

- *Wetlands*: cleaning up oiled wetlands is virtually impossible, since both oil and efforts to remove it can kill coastal plants. The Gulf's wetlands are a natural buffer against hurricanes. On top of BP's spill and the threat of others, the Gulf Coast must also deal with rising seas and stronger storms as a result of the climate change.
- *Seabirds*: federal scientists counted more than 6,000 birds killed by oil in the first year alone, while 1,250 were cleaned and released. The hardest-hit species were the laughing gull, and brown pelicans.
- *Sea turtles*: about 240 sea turtles are stranded along the US Gulf Coast in a typical year, but more than 1,100 turned up during the BP spill's first year – including 450 visibly oiled and 600 dead or dying. The death rate is lower now, but has remained high enough to push the estimated three-year death toll past 1,700. Plus, as with birds, it is noted that 'only a very small portion of dead sea turtles are ever found.'
- *Marine mammals*: Whales and dolphins (Cetaceans) in the northern Gulf have been dying in droves for the past 3 years, leading NOAA to formally declare an Unusual Mortality

Event (UME). As of April 2013, the UME involves 930 cetacean strandings, 95% of which were found dead. The die-off actually started in February 2010, two months before the BP spill, but its length and severity have raised concerns that oil made things worse. In Barataria Bay (Louisiana) dolphins have severe health problems that are not showing up in dolphins from the un-oiled area, and have not been seen in previous studies of dolphins from other sites, according to NOAA.

- *Fish*: Several fish kills struck the Gulf Coast in the spill's wake. Reports of fish with open sores, strange black streaks and other deformities have continued years later. Yet linking this to oil has been difficult, and authorities say Gulf seafood is now safe. Fishing bans were lifted in the spill's first year, and many Gulf fisheries are returning to normal.
- *Crustaceans* (including lobsters, crabs and shrimp): The oil spill hurt countless shrimp, crabs, copepods and other crustaceans. Shrimp losses were especially hard on the region's famous seafood industry that dates back more than 200 years. But according to the National Wildlife Federation (NWF) shrimp are now one of the few bright spots in the Gulf's recovery.
- *Microbes*: The microbes may be among the most important actors. The researchers have focused closely on the Gulf's oil-eating bacteria. The microbes normally use this ability to get energy from natural oil and gas seeps, which are relatively small, but they swept into action when their habitat was flooded with crude. The researchers have been tracking evidence of this, discovering new layers of seafloor sediment created by 'marine snow,' or organic debris that sank from the microbes' oily feasts. The broad use of chemical dispersants in 2010 – often credited with preventing larger, thicker blobs of oil from reaching shore – may have been unnecessary, and possibly unwise. The Gulf already has a natural mechanism for breaking down oil, but BP and US officials embraced dispersants like Corexit without controlled experiments to prove their benefit. A recent study found that mixing Corexit with oil can make the oil 52 times more toxic to plankton. This damage to the plankton could harm the food chain in ways that won't show up for years. Samantha Joye, University of Georgia, a leading researcher in ECOGIG on the consequences of the spill: 'I'm very nervous about using dispersants as a first line of defense in an oil spill, but I worry that's the mentality we're headed toward.'
- *Humans*: Eleven people died in the initial explosion that destroyed the rig. Thousands upon thousands of people have also been affected in the first 3 years in a wide range of ways. Some were physically sickened by oil or its fumes during the cleanup. Others lost fortunes or entire businesses to prolonged slumps in fishing, shrimping and tourism.

President Obama said in June 2010: 'In the same way that our view of our vulnerabilities and our foreign policy was shaped profoundly by 9/11, I think this disaster is going to shape how we think about the environment and energy for many years to come'. Yes, indeed!

Federal officials in the US announced (October 2014) that about 44 million acres (178,000 km^2, somewhat larger than the area of Florida) in the Gulf of Mexico will be opened to oil and gas drilling early in 2015. The waters stretch from 8 to 425 km off the coast in the central Gulf, and depths run to around 3,300 m. Some of the leases are within 5 km of the US nautical border with Mexico (Eco Magazine, 2014).

Risk and responsibility

One of the problems with the reliability of the energy operations is a common fragmentation of responsibility. BP had the responsibility for the operation of Deepwater Horizon. BP leased the platform from Transocean, and Halliburton was doing the deep-water work when the blowout occurred. These corporations have different goals. BP aims to obtain the oil and gas for their energy refining, distribution and sales. Halliburton provides oil field services ('we just acted on orders from BP'). Transocean drives drill rigs. They all have different operating processes.

Another serious problem is the failure of risk analysis. The risks that are assessed are catastrophic events that will happen very seldom. They cannot be estimated by simple check lists on a daily or weekly operational basis. There may be decades before a major disaster will happen. Consequently catastrophic events may be so unlikely that they are not worth a serious attention. In the USA the energy corporations have lobbied to avoid making formal analysis of worst case scenarios. The Carter administration first required them in instances where there was uncertainty about the risk of a catastrophe.

As long as there is a large thirst for oil the industry will probably take too large risks. More environmentally conscious oil and gas exploration would cost more and the oil price would probably go up. However, there would be a lot of profits: cleaner environment, less probability for accidents and a slower economy that might dampen the greenhouse gas emissions.

11.3.2 Exxon Valdez, Prince William Sound, Alaska, 1989

The tanker Exxon Valdez struck a reef in Prince William Sound, Alaska on Good Friday 24 March 1989 and some 43,000 m^3 (0.25 million barrels) of oil assaulted the Sound (Hodgson-Fobes, 1990). An army of 11,000 men and women pitted against the worst ever US tanker spill. In May about 180 workers attacked the stricken shore of Green Island with high-pressure hoses to break up the tarry residue and wash it to the water's edge for collection. Such methods, however, sometimes kill shoreline organisms. Exxon Corporation, responsible for the oil and its tanker was compelled to pay the state and federal governments more than US$ 1 billion in criminal and civil damages. Although volunteers struggled to save oiled seabirds, it is estimated that the oil spill killed between 350,000 and 600,000 birds, including some 150 bald eagles (the symbol of the US). At least a thousand sea otters had perished. Throughout the sound and down the Gulf of Alaska as far as lower Cook Inlet and Kodiak Island, the damage had been staggering. Oil had drenched or spattered at least 1900 km of shoreline.

It is interesting to note the 'defense' organization to combat any spill. The Alyeska Pipeline Service Company – located some 50 km from the accident – had with the approval of the Federal Government assembled equipment for use in 'the most likely spill' of about 150–300 m^3 (1000–2000 barrels) while the real spill was 43,000 m^3. Actually, at a congress hearing after the accident, Alyeska experts had dismissed the possibility of a 30,000 m^3 (200,000 barrels) spill as something that might happen once in 241 years (note the accuracy!). There is a saying in Alaska that 'only one in 100 brown bears will bite. The trouble is that they don't come in numerical order'.

After ten years it was reported that less than 15% of the spill was recovered (Mitchell, 1999). Most of the oil evaporated or biodegraded, but what remains is tenacious. Waves easily wash sandy beaches clean. However, the oil can remain beneath and between rocks, sheltered from the surf. Marshes and mudflats hold oil even tighter. Their fine sediments keep the oxygen out – and with it the microorganisms that break oil into nontoxic elements. In order to promote the growth of microorganisms naturally present in the environment that break down oil bioremediation was applied. A nitrogen-phosphorous fertilizer mix was sprayed on an oil-laden shore in hopes of stimulating oil-eating bacteria. Such technique has been employed against toxic wastes.

It is obvious that the environmental and human sufferings are enormous after an oil spill. The killing of animals, birds, and fish is not only a catastrophe in itself. It mostly affects the living conditions of the people, depending on for example fishing (Peterson *et al.* 2003). This book, however, will not elaborate on these issues. Also, in the Exxon Valdez case no direct drinking water supplies were affected, but it certainly demonstrated how oil spills will spoil the water quality. After the accident Exxon has made huge efforts to integrate safety in almost every aspect of operations.

Between 1970 and 1999 some 50 spills of the size of Exxon Valdez or larger have happened worldwide.

11.4 OIL EXPLORATION IN NIGERIA

> *Poverty is the worst form of violence.*
>
> M. Gandhi

The Niger Delta is the hub of oil production in Nigeria. The Delta holds massive oil deposits, which have been extracted for decades by the Government of Nigeria and by multinational oil companies. The environmental consequences of the oil exploration in the Niger Delta have made much smaller headlines than the Western accidents. The suffering of the population in the Niger delta as a result of the oil exploration has been observed by the United Nations and other international organizations (UNEP, 2011b; Amnesty International, 2009, Amnesty International and CEHRD, 2011). As expressed in UNEP (2011b): 'most members of the current Ogoniland (eastern part of the Niger Delta) community have lived with chronic oil pollution throughout their lives.' Oil pollution, mostly caused by equipment failures and oil theft, substantially degrades the Delta network of alluvial swamps and lands, creeks and rivers. The oil industry is a major contributor to the environmental catastrophe, and moreover, has been for more than half a century. Shell Petroleum Development Corporation (SPDC), a subsidiary of Royal Dutch Shell, is the main operator on land. SPDC alone operates over 31,000 km^2 (Amnesty International, 2009).

The Niger Delta is one of the ten most important wetland and coastal marine ecosystems in the world and is home to some 30 million people. It is the largest river delta in Africa and the third largest in the world. Oil has generated an estimated US$ 600 billion since the 1960s (Wurthmann, 2006). Despite this, the majority of the Niger Delta's population lives in poverty. The United Nations Development Programme (UNDP, 2006) describes the region as suffering from 'administrative neglect, crumbling social infrastructure and services, high unemployment, social deprivation, abject poverty, filth and squalor, and endemic conflict.' UNDP also declares that 'the Niger Delta has an enormously rich natural endowment in the form of land, water, forests and fauna. These assets, however, have been subjected to extreme degradation due to oil prospecting. For many people, this loss has been a direct route into poverty, as natural resources have traditionally been primary sources of sustenance.' The majority of the people of the Niger Delta do not have adequate access to clean water or healthcare. Their poverty, and its contrast with the wealth generated by oil, has become one of the world's starkest and most disturbing examples of the 'resource curse'.

11.4.1 Magnitude of oil spills in the Niger Delta

Several attempts have been made to estimate the number of spills and volume of oil spilt onshore and offshore in the Niger Delta since the oil industry began operations in the late 1950s. Estimates vary but put the number at over 10,000 spills (UNEP, 2011b). There is no consensus on the number of oil spills and volume of oil spilling into the Delta environment, as the operating companies and Government of Nigeria keep conflicting data. However, UNDP has put the *annual* average number of oil spills and volume spilled into the Delta environment between 18,000 and 44,000 m^3, making the Delta one of the most oil spill vulnerable areas in the world. As expressed by UNDP (2006, page 92): 'The oil companies, particularly Shell Petroleum, have operated for over 30 years without appreciable control or environmental regulation to guide their activities.' The report also notes that 'it is doubtful whether the Government's environmental monitoring agencies can adequately control the activities of the oil companies' (Ibid.). Given the long history of spills and other problems, both the companies and the Government should have recognized the need for adequate monitoring systems a long time ago. This was expressed in 2006. Below we look at the situation in 2014.

Spill figures vary considerably depending on sources, and figures are contested. Only SPDC reports publicly, from year to year, on the number of spills in its operations. Between 1989 and 1994 the company reported an average of 221 spills per year involving around 1200 m^3 of oil per year (Amnesty International, 2009). The Department of Petroleum Resources (DPR) has reported that 4835 oil spill incidents were recorded between 1976 and 1996, with a loss of some 290,000 m^3 of oil to the environment. These data are based mainly on what companies report to the DPR. According to NOSDRA (National Oil Spill Detection and Response Agency in Nigeria) more than 6800 spills were recorded between 1976 and 2001, with a loss of approximately 480,000 m^3 of oil. In the period between 2007 and 2012 NOSDRA has recorded almost 3,000 oil spills.

Drawing on available data, a group of independent environmental and oil experts visiting the Niger Delta in 2006 put the figure for oil spilt, onshore and offshore, at 1.4–2.1 million m^3 of oil over the past 50 years, or some 28,000–42,000 m^3 per year during 50 years (Niger Delta, 2006; Amnesty International, 2009, Amnesty International and CEHRD, 2011). The experts took into consideration all sources of oil discharged into the environment, including oil in process water, oil discharges from tanker washing, oil in gas flares, oil spills from vehicle and road tanker accidents and used oil dumped in the Delta, as well as spills during the Biafran war, when many oil installations were either bombed or sabotaged. To put this into perspective, people living in the Niger Delta have experienced oil spills on par with the Exxon Valdez every year over the last 50 years in a very ecologically sensitive area. Many commentators believe both the number of oil spills and volume of oil spilt are under-reported.

The Niger Delta has been suffering one 'Exxon Valdez oil spill' every year for 50 years – without proper remediation or financial compensation.

Volume estimates of oil spills are usually low as 50% of Nigerian oil is assumed to evaporate within 48 hours and spills are not usually detected in that period. Most spills in the Delta are left unattended. It is clearly documented that the oil industry has conducted its petroleum operations in Nigeria far below commonly accepted international practice used elsewhere in the world – a double standard (Niger Delta, 2006; Steiner, 2010; Zabbey, 2009a, 2009b; Eregha-Irughe, 2009; Patin, 1999). As documented in Niger Delta (2006): 'Oil companies operating in the Delta … can easily improve their environmental performance in the region. Old leaking pipelines and installations must be replaced immediately and dumping of waste must stop.'

The spills have not come to a halt. Table 11.3 shows the number of oil spills in recent years. Nigerian Agip Oil Company, a subsidiary of the Italian company ENI, has caused 1,668 spills in less than 4 recent years, while Shell have some less. Agip attributes the vast majority of spills to sabotage but provides absolutely no information to support this allegation (Amnesty International and CEHRD, 2013, from NOSTDRA database).

Table 11.3 Recent number of oil spills in Nigeria.

Year	Agip on NOSDRA database	Shell on NOSDRA database	Shell on Shell's website	Total Shell + Agip NOSDRA database
2010	323	188	170	511
2011	400	207	207	607
2012	474	207	192	681
2013 to end Sep.	471	138	138	609
Total 2010–2013	1668	740	707	2408

Sources: NOSDRA database and Amnesty International and CEHRD, (2013), p. 10.

Quoting Audrey Gaughran, Director of Global Issues at Amnesty International (Amnesty International and CEHRD, 2013): 'These spills are caused by corrosion, poor maintenance of oil infrastructure and equipment failure as well as sabotage and theft of oil. The Niger Delta is the only place in the world where companies brazenly admit to massive oil pollution from their operations and claim it is not their fault. Almost anywhere else they would be challenged on why they have done so little to prevent it.'

In 2004 the pipeline failure rate per 1000 km-year was 0.43 in Western Europe, compared to 6.40 in Nigeria, 15 times higher (Steiner, 2010). Between 2006 and 2010 the Trans-Niger Pipelines (TNP) suffered an incidence of operational oil spills at a rate of more than 130 times greater than the European average (Zabbey, 2014). Shell has consistently refused to disclose the age or condition of its pipelines. For years Shell has blamed the massive oil pollution associated with its operations on theft of oil and other illegal activities. But the company has taken almost no effective action to prevent the theft of oil and secure its pipelines.

11.4.2 The Bodo Creek incidents 2008–2009

Just one place out of many places affected by oil spills may illustrate the situation. The presence of active Trans-Niger Pipelines (TNPs), transporting crude oil from the hinterlands through Ogoni, eastern Niger Delta, to Bonny crude oil terminal remains potential threats of oil spillages. The Bodo Community is situated on the north east edge of creeks and mangrove wetlands known as the Bodo Creek. Many of the TNPs traverse Bodo Creek. Bodo is a rural coastal settlement consisting of the Bodo city and surrounding villages with a population of around 50,000 people. The majority of its inhabitants are subsistence fishermen and farmers. On 28 August 2008 a fault in the TNP caused a significant oil spill into Bodo Creek (CEHRD, 2008; Zabbey *et al.* 2010; Pegg-Zabbey, 2013).

The oil poured into the swamp and creek for weeks, covering the area in a thick slick of oil and killing the fish that people depend on for food and for their livelihood. Shell Petroleum Development Company (SPDC) was responsible for the pipeline that broke. The community claims that the spill began on 28 August 2008. SPDC stated that the incident was reported to them on 5 October. The said pipeline is situated below ground and the crude oil at first saturated the surrounding soil and waterways. As the water level rose, the crude oil was carried to the surface of the creek and was then spread by tidal waters across the Bodo creek and to neighboring communities. The Ministry of Environment was informed on 12 October. It took the oil company over a month to repair the weld defect in the pipeline and the leak was not stopped until 7 November. According to Shell 1,640 barrels (260 m^3) of oil were spilled in total. However, experts consulted by a UK legal firm have estimated that as much as 4,000 barrels (>600 m^3) of oil *a day* were leaking from the pipe, at least 60 times the Shell data (Amnesty International and CEHRD, 2013).

A second spill occurred on December 7, 2008 and was also the result of equipment failure, further damaging the environment on which people depend for their food and livelihood. The spill lingered on till 21 February 2009, when it was jointly investigated and clamped. In this second spill, Shell estimated that 2,503 (notice the alleged precision!) barrels (400 m^3) of oil were spilled, covering an area of 1 hectare. The method of calculation is not clear. According to the Joint Investigation Visit (JIV) report and the Bodo community, the second spill was larger than the first. Independent experts have estimated the two spills to have been 80,000–95,000 m^3 (500,000–600,000 barrels) before the pipes in Bodo were clamped (Amnesty International, 2009).

On 2 May 2009, eight months after the spill, SPDC staff reportedly brought food relief to the community, which they rejected as wholly inadequate. According to Dr. Nenibarini Zabbey (email in 2009), head of the Environment and Conservation Program at the Center for Environment, Human Rights and Development (CEHRD, Port Harcourt, Nigeria): 'SPDC officials arrived at the palace of the paramount ruler of Bodo on Saturday 2 May, 2009, and presented as relief materials 50 bags of rice, 50 bags of beans, 50 bags of garri (a cassava product), 50 cartons of sugar, 50 cartons of dry peak milk, 50 cartons of milo tea, 50 cartons of tomatoes and 50 tins of groundnut oil. The Bodo population is little above 69,000. Given the population figure, the Bodo people consider the offer by SPDC as insulting, provocative and beggarly, and unanimously rejected the items.'

It has been estimated that 1,000 hectares of mangroves were destroyed by the spills and a further 5,000 hectares were impacted, the largest loss and damage to mangroves by oil the world has ever seen. (High Court of Justice, 2012; Dr. Erich Gundlach of E-Tech International Inc., a specialist oil spill response organization). Since the oil spills 13,000 fishermen from the Bodo community have been unable to continue working.

In 2006, independent Nigerian, British and USA environmental experts had conducted a preliminary Resource Damage Assessment in the Niger Delta for the Nigerian Federal Ministry of Environment. The independent assessment found that many of the oil facilities and operations are located within sensitive habitats, including areas vital to fish breeding, sea turtle nesting, mangroves and rainforests, which have often been severely damaged. The report states that the damage from oil and gas operations is '*chronic and cumulative and has compromised livelihoods* . . .' (High Court of Justice, 2012).

The Bodo Creek remains totally contaminated even six years after the spills started. A UN report (UNEP, 2011b) reveals high level hydrocarbon contamination of surface and groundwater and at one particular location, benzene concentration in local drinking water was found to be over 900 times the WHO limit. Oil-related pollution has impacts on health and biodiversity that the people's livelihoods depend upon (Hart *et al.* 2007; Zabbey *et al.* 2010). An impact assessment of the two large oil spill incidents at Bodo Creek was undertaken, focusing on intertidal macrozoobenthos (Zabbey-Uyi, 2014). Zoobenthos are the most preferred indicator fauna used in the evaluation of environmental quality of aquatic ecosystems, owing to their longevity, abundance, diversity, large sizes and relative immobility. Post-spill number of species and abundance were measured against recent pre-spill baseline data from the same study area. Results show that surface and infauna communities suffered severe reduction in abundance and number of species reduced by 81% after the spills, with two of the resampled sites having no taxa at all. The impact of oil pollution includes, but is not limited to, high mortality of plants and animals, loss of biodiversity in breeding grounds, reduction in fishing and farming activity, impairment of human health, food insecurity and poverty, impairment of growth and reproductive outputs. In 2011 Shell admitted liability for the spills but continues to dispute the amount of oil spilled and the extent of the damage caused.

The public health problems are serious, according to UNEP (2011b). The UN report is an ambitious independent scientific study of the impacts of oil pollution in the Niger Delta. The report reveals the devastating human and environmental effects of decades of oil spills in the area. It also refers to raised concentrations of petroleum hydrocarbons in the air and drinking water. The long-term effects are not yet well understood, but could include cancer and neurotoxicity. No health monitoring was done in Bodo and the people fear about the health implications of living in close contact with crude oil. UNEP (2011b) noted: ‘Petroleum hydrocarbons can enter people's bodies when they breathe air, bathe, eat fish, drink water or accidentally eat or touch soil or sediment that is contaminated with oil.’

11.4.3 Produced wastewater

As in any oil exploration and operation there are big volumes of produced (waste)water. In the Niger Delta the produced water has polluted land and water, damaging fisheries and agriculture (Amnesty International, 2009), undermining the human right to an adequate standard of living. According to an interview by Amnesty researchers (Amnesty International, 2009) with a senior official from the Rivers State Ministry of Environment: ‘Effluent and waste from the oil industry which should be treated is dumped and finds its way into the surface water of the Delta …’. Much of the produced water is discharged into rivers and the sea without any treatment. Hundreds of tons of oil together with other potentially toxic substances are released into the Niger Delta as wastewater. In 2009 Amnesty found little evidence that either the companies or the Government were monitoring the impact on water quality, fisheries or human health. Nonetheless, some companies appear to be aware that the discharge of produced water is not a good practice. Figures from SPDC for 2002–2005 show a significant rise in oil discharged to surface waters as a consequence of produced water – from 226 tons of oil in 2002 to 481 tons in 2005. Still the volume of produced wastewater decreased from about 43 million m^3 in 2005 to just below 17 million m^3 in 2006. On the other hand, the average oil in surface water increased from 8.5 mg/l in 2002 to 17.8 mg/l in 2006 (SPDC, 2006, p. 18). Another major source of wastewater is drilling, which produces large amounts of mud and dry cuttings. Drilling waste has frequently been disposed of indiscriminately, often into drainage channels and waterways, which affects water quality, or on to land used for agriculture.

11.4.4 Environmental impact after 2009

Amnesty International and CEHRD (Nigeria) have continued the investigations after the spills not only in Bodo but also in other places in the Niger Delta. Several reports have been published but Amnesty International and CEHRD (2011) demonstrates with photos and satellite pictures the scale of the environmental impact of the 2008 spills. Shell has so far failed to clean up the polluted areas, despite the requirements of Nigerian oil industry regulations. In 2011 the people of Bodo began a court action in the United Kingdom (UK), see below.

Following international media reports in August 2011 about its ongoing failure to clean up after the two Bodo spills, Shell issued the following statement (April, 2011): 'No matter what the cause, Shell is committed to stopping and containing all spills, recovering and cleaning up as much oil as possible and restoring sites in compliance with regulations as quickly as possible.' However, this statement did not explain why, almost three years after both spills, this had not already happened. It is also unclear why the Nigerian Government's regulatory agencies have not taken action to compel Shell to comply with national regulations.

A US diplomatic cable from 2008, published by Wikileaks in 2011, stated that a contractor with many years of experience of laying pipelines in the Niger Delta told the US consulate that '73% of all pipelines there are more than a decade overdue for replacement. In many cases, pipelines with a technical life of 15 years are still in use 30 years after installation'. 'Because the equipment is corroded and relatively close to the surface, making it more vulnerable to intentional and unintentional damage from natural and human causes, spills occur daily, and it often takes many hours to find the location of the spill and deploy the necessary clean-up equipment.' (Amnesty International and CEHRD, 2011, p. 35).

On or close to 21 June 2012 still an oil spill was discovered in the Bodo creek area of the Niger Delta. Shell is responsible for the pipeline at Bodo. A joint investigation was initiated on 30 June. An independent investigator with more than 10 years of pipeline industry experience concluded that there was evidence of a corrosion failure. As of September 2013 Shell had yet to remove the affected area of the pipe and the JIV was not complete (Amnesty International and CEHRD, 2013, p. 26).

11.4.5 Restoration

Access to information and disclosure of the facts is central to the right to remedy. The entire process surrounding oil spills in Nigeria lacks transparency (Amnesty International and CEHRD, 2011). Lack of data makes is difficult to assess the scale of the impact of oil spills on agriculture and fishing. However, one major indication of the impact on soils is the number of sites that need to be remediated (where both the Government and the oil companies recognize that restoration is required). In 2008 there were at least 2,000 such sites in the Niger Delta (Amnesty International, 2009). The Nigerian Government guidelines (Department of Petroleum Resources) from 2002 stipulate than clean-up should commence within 24 hours of the occurrence of the spill. The guidelines (§2.11.3) also stipulate that for all waters 'there shall be no visible sheen after the first 30 days of the occurrence of the spill no matter the extent of the spill.' Indeed! Shell has an obligation to clean up all oil spills, *regardless of cause*.

The UNEP (2011b) report is an extensive assessment of the consequences of the oil exploration. Even though the oil industry is no longer active in Ogoniland, oil spills continue to occur with alarming regularity. The Ogoni people live with this pollution every day. In 49 locations, UNEP observed hydrocarbons in soil at depths of at least 5 m. This finding has major implications for the type of remediation required. The UNEP investigation found that the surface water throughout the creeks contains hydrocarbons. Floating layers of oil vary from thick black oil to thin sheens. The wetlands around Ogoniland are highly degraded and facing disintegration. Remediation by enhanced natural attenuation (RENA) – so far the only remediation method observed by UNEP in Ogoniland – has not proven to be effective. Currently, SPDC applies this technique on the land surface layer only, based on the assumption that given the nature of the oil, temperature and an underlying layer of clay, hydrocarbons will not move deeper. However, this basic premise is not sustainable as observations made by UNEP show that contamination can often penetrate deeper than 5 m and has reached the groundwater in many locations.

The UNEP (2011b) report calls for an Environmental Restoration Fund for Ogoniland should be set up with an *initial* capital injection of US$ 1 billion contributed by the oil industry and the Government. The environmental restoration of Ogoniland may take 25–30 years, and this can be elaborated for the entire Niger Delta. Environment groups and Ogonis have welcomed the UNEP report but said US$ 100 billion will be needed to clean up the entire delta, beyond just Ogoniland. Several coastal ecosystem restoration models may be of use and have been applied in other places (Niger Delta, 2006), for example: (1) UNEP (UN Environment Programme) Damage Assessment and Restoration Framework, (2) NRDA (Natural Resource Damage Assessment), employed by the Deepwater Horizon spill in the Mexican Gulf, (3) Exxon Valdez Oil Spill Restoration Program. This amount of restoration money would be comparable with the money set aside for the Deepwater Horizon accident. The great difference is that the funding for the Mexican Gulf cleanup was decided soon after the accident. The Nigerian people still have to wait.

11.4.6 Legal actions and human rights

The Niger Delta is a complex operating environment, characterized by conflict – conflict within and between communities (often related to access to the benefits of oil operations), conflict between the communities and the oil companies and conflict between armed groups and the oil companies and Nigerian security forces. As Amnesty International (2009) describes, the complexities that the oil companies face should be acknowledged. However, it is too often used as an excuse for failure to take action in line with international good practice. Under Nigerian law, local communities have no legal rights to oil and gas reserves in their territory. The Federal Government allocates permits, licenses and leases to survey, prospect for and extract oil to the oil companies, who are then automatically granted access to the land covered by their permit, lease or licence. There are cries for justice by the impacted communities of the Delta. The Bodo Creek has been destroyed for more than a generation. Amnesty International (2009) describes the Ogoni struggle for justice in the 1990s. On 8 June 2009 Shell and the plaintiffs reached a settlement. Shell agreed to pay the plaintiffs US$ 15.5 m. The company did not admit any liability. Shell described the settlement as a humanitarian gesture.

In a legal action evidence was presented from research carried out just before the spills (Onwugbuta-Enyi *et al.* 2008). This research had shown that the main river channels in the Bodo creek had no physical trace of oil, were 'near pristine', were rich in fauna and free of hydrocarbons. Following the two spills, in September 2009, a Post Impact Ecological Assessment study of the oil spillages was carried out on the Bodo creek. This found a severe reduction in the abundance of marine life with shellfish no longer present and fish numbers dramatically reduced. (Leigh, Day & Co, 2014). The Bodo community also claims that the pipeline, which caused the devastating leaks, is over 55 years old and should have been replaced many years ago.

It is a painful comparison to consider the legal actions to compensate the damages in the Niger Delta and around the Mexican Gulf after 2010. As Amnesty International (2009) reported: the penalties for failing to report an oil spill to NOSDRA is around US$ 3,500. The fine for failure to clean up the impacted site ‘to all practical extent, including remediation’ incurs a fine of around US$ 7,000. The informal compensation system lacks transparency. The amounts paid are not made public and it is not clear to whom compensation is paid (Amnesty International, 2009, p 72).

The legal system imposes specific limitations on the plaintiff’s ability to sue a company for oil damage (Amnesty International, 2009, p 75). Negligence is the most frequently used tort to pursue action against oil companies. However, the law requires that the plaintiff must show that the defendant was careless in the exercise of a specified duty of care. The plaintiff bears the burden of proof. This can be a very difficult burden, given the technical nature of oil operations and the fact that technical evidence is frequently either very expensive to obtain or held by the defendant and on which the defendant is significantly more knowledgeable. Usually only the defendant (the oil company) has the data.

So far (2014), the people of Bodo have been paid no official compensation for their losses resulting from the oil spills. The Bodo community has tried to secure compensation and sought legal advice in 2009. The community’s Nigerian lawyer wrote to Shell in April 2009 demanding immediate remediation and US$ 129 million in compensation for the losses incurred. In response, Shell did not refer to the claim, but wrote that the August 2008 spill was caused by ‘unknown third parties’ (Amnesty International and CEHRD, 2011, p. 21). In April 2011, the Bodo community decided to make a bid for justice before the High Court in the UK. In August 2011 it was announced that Shell (SPDC) had formally accepted liability in the UK’s jurisdiction.

In January 2013 a Dutch court, the District court in The Hague, dismissed most of the claims brought by Nigerian farmers seeking to hold Royal Dutch Shell accountable for damage caused by oil spilled from its pipelines. The company had argued that the oil spills were not its fault, but a result of criminal tampering (Int. Herald Tribune, 31 Jan. 2013).

After many years, however, it looks as if Shell can be held for devastating oil pollution in the Niger Delta. In a judgment delivered by Mr. Justice Akenhead, the London Technological and Construction Court found that short of providing policing or military defense of its pipelines, Shell was responsible for taking reasonable steps to protect them. This would include measures such as installing leak detection systems, surveillance equipment and anti-tamper equipment (Amnesty International Press release 20 June 2014, www.amnesty.org). The ruling comes as part of a civil claim brought by people from the Bodo community and has opened the door for Nigerian claimants to demand compensation if oil leaks were a result of sabotage or theft – if the sabotage or theft was due to ‘neglect on the part of the (license) holder or his agents, servants or workmen to protect, maintain or repair any work structure or thing.’

The lack of leadership that will defend the rights for all the people suffering is upsetting. As a party to the International Covenant on Economic Social and Cultural Rights (ICESCR, the Covenant; see ICESCR, 2014), Nigeria is under an obligation to ensure the availability of sufficient, safe, acceptable water for personal and domestic uses. The situation in the Niger Delta boils down to a lot of human rights violations, one being the right to water (see Chapter 1). This occurs when oil spills and waste materials pollute water used for drinking, other domestic purposes, and for fishing and agriculture. According to the Amnesty International expert group the people of the Niger Delta have seen their human rights undermined by oil companies that their Government cannot or will not hold to account. They have been systematically denied access to information about how oil exploration and production will affect them, and are repeatedly denied access to justice. The fact that Nigeria's regulatory bodies cannot, or do not, function properly has left the people of the Niger Delta with nowhere to turn.

11.4.7 Court decision 2015

Only a few days before this book manuscript is sent to the publisher (January 2015) Shell has agreed to pay the Bodo community £ 55 million for the oil spills in 2008. Out of this, £35 million goes to the individual claimants, while the balance of £20 million is the community claim that can be spent on basic amenities in the community. The hope is that this could open a floodgate of litigations in Niger Delta and in other places. The agreement is the end of a three year legal battle. Shell Nigeria is 55% owned by the Nigerian government. The agreement is a significant and precedent-setting development that 'will create huge expectations among the communities of instant transformation of their lives from poverty to opulence', according to Professor George Frynas, professor at Britain's Middlesex University Business School, who has closely studied these conflicts.

Shell also has agreed to a long-overdue cleanup, but a UN report has said it could take 30 years to properly restore the ruined mangrove swamps.

11.5 OIL EXPLORATION IN THE ARCTIC SEA AND IN RUSSIA

> *Sometimes something has got to happen before something is going to happen.*
> A 'Cruyffian' phrase from the Dutch footballer Johan Cruyff

As the vast resources of the Arctic Sea opens up for the oil industry as a result of the climate change it has become obvious that no country is fully prepared for an oil spill in the region (NRC, 2014). The National Academy of Sciences has taken a comprehensive look at the impact of oil and gas exploration in the Arctic. In the intervening decade, sea ice cover hit a record low, shipping traffic increased dramatically, and the price of oil rose sharply. This stimulated companies as Shell, ExxonMobil, and ConocoPhillips to acquire new leases for oil and gas. The Arctic contains an estimated 13% of the world's undiscovered oil. Shell made an attempt to drill into it in 2012 and this illustrated the challenge of working in the Arctic. The campaign ended with the drilling rig, the *Kulluk*, running aground and needing to be rescued. Shell and other companies have suspended Arctic drilling plans for 2014, but there is little doubt the push to develop the region's energy resources will continue. The NRC report reminds not only about the *Kulluk* incident but also of the BP Deepwater Horizon and Exxon *Valdez* disasters.

There is no proven effective method for containing and cleaning up an oil spill in icy water (Ernst & Young, 2013):

- *Response time to a spill*: the difficult conditions of the Arctic, and its distance from where response capacity is stationed mean it can take days or weeks to respond to a spill, even during ice-free periods.

- *Slow spill recovery*: the Arctic has a short productive season, low temperature and limited sunlight. Therefore it can take decades for Arctic regions to recover from oil spills and tundra disturbance.
- *Important wildlife and fishing*: offshore oil exploration, drilling and production can disturb the fish and animals that are cornerstones of the livelihoods of Indigenous peoples in the Arctic.

During the last few years the oil and gas industry growth in the Arctic Zone of the Russian Federation (AZRF) has increased. Environmental threats, as well as threats to indigenous peoples inhabiting the area and their traditional way of living, have grown accordingly. It has been apparent that safety and environmental protection have not got high priority. Greenpeace has investigated and documented the ongoing disaster (Greenpeace Russia, 2012a, 2012b). Inadequate investments in the safe operation of oil and gas exploration and production result in huge quantities of oil spilled within the environment of the Arctic zone. Russian sources have reported more than 20,000 oil leaks per year during 2010 and 2011. Poor design and maintenance of highly stressed pipe lines is a major issue. Frequently oil companies either do not have the actual data on spilled oil volumes or hide it.

Tens of thousands of small-scale leaks from pipelines throughout the Russian oil fields result in millions of tons of oil polluting the landscape every year. Extreme weather conditions in Siberia along with lack of maintenance have resulted in a slow but constant seepage of oil from pipeline ruptures. In the long Arctic winter, oil leaks unnoticed from numerous underground pipeline ruptures. With the rising temperatures in summer, huge amounts of oil are flushed with the melt-water into the rivers. Russian expert assessments of oil product concentrations in Siberian rivers lead Greenpeace to conclude that, *at least*, 5 million tons of oil products are released into the environment annually. This spill rate is about 6 times greater than the volume of the 2010 Gulf of Mexico spill and 2–3 times the accumulated oil spills in the Niger Delta. It is further estimated that *at least* 500,000 tons of oil from these spills are annually carried by Siberian Rivers to the Arctic seas. This makes the Russian oil spills more devastating than any other spill in the world. It becomes not only a Russian problem but everyone's problem.

Figure 11.3 illustrates the oil pollution carried northwards by the four major Siberian Rivers. For example, the river Ob' runs (with a flow rate of more than 12,000 m^3/s) through very big oil fields in Western Siberia and carries more than 100,000 tons of oil products northwards. Together the rivers transport more than 400,000 tons of oil products into the Arctic Sea.

The Arctic Sea is cold, which makes it an extremely sensitive environment. This current reckless decades-old common practice of oil spills from land based Russian oil exploration makes the perspective of Arctic shelf development a frightening perspective. The risks for significant oil spills at sea are apparent. There is no reason to trust that Russian oil and gas industry will be less reckless in the oil exploration in the Arctic Sea.

As in Nigeria corruption is a very dangerous disease in the Russian society. In 2014, both Russia and Nigeria scored 27 or number 136 out of 175 countries as to the perception of corruption of its public sector, where 0 means that a country is perceived as highly corrupt and 100 means that a country is perceived as very clean (Transparency International, 2012).

All expenses connected with the 2010 Gulf of Mexico accident were assessed by BP at more than US$ 40 billion (see 11.3). The mitigation and clean-up costs of a 2010 Gulf of Mexico equivalent oil spill within the Arctic offshore will certainly be much higher than the

2010 Gulf of Mexico oil spill. There is insufficient infrastructure to quickly and efficiently initiate clean-up work. All together more than 6,500 ships took part in the mitigation works in the 2010 Gulf of Mexico oil spill where the infrastructure is far more developed than in any Arctic region. In the Arctic offshore, there is no such infrastructure, and none which is approved by either Russian or US authorities. For example, as Greenpeace Russia (2012b) reminds: the nearest federal rescue station and necessary infrastructure from the 'Prirazlomnaya' platform – the world's first maritime ice-resistant stationary platform – are located in Murmansk, about 1000 km from the platform. The existing Prirazlomnaya insurance for potential ecologic damage is about US$ 230,000.

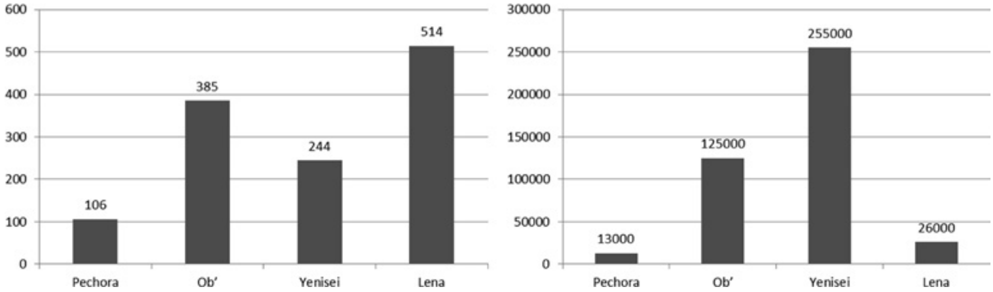


Figure 11.3 Oil and oil products released annually via the major Siberian Rivers. The left diagram shows the annual flow in km^3 (the Lena flow of 514 km^3 corresponds to 16,000 m^3/s) and the right diagram shows the total mass of oil (tons) per year. The average concentrations of oil products are 0.1 mg/l (Pechora), 0.35 mg/l (Ob), 0.4 mg/l (Yenisei) and 0.05 mg/l (Lena). The maximum allowable concentration for water of commercial fishing importance is 0.05 mg/l in all the rivers. (*Source*: Greenpeace Russia (2012b)).

The Lloyd insurance company warns (see Kollewe-MacAlister, 2012) that cleaning up any oil spill in the Arctic, particularly in ice-covered areas, would present 'multiple obstacles, which together constitute a unique and hard-to-manage risk. The Lloyd report (Emmerson-Lahn, 2012) estimates that US$ 100 billion of new investment is heading for the Far North over the next decade. The report notes that there is no international liability and compensation regime for oil spills.

11.5.1 A human rights issue

Indigenous groups of the North, Siberia and the Far East of Russia (totaling about 250,000 people) are one of the most vulnerable parts of the Russian society. They depend directly on fishing, hunting, deer farming and gathering. Consequently, the development of extractive industries and forest industrialization catastrophically affects their traditional territories. Many indigenous people are forced to leave these territories.

Oil and gas projects within the Russian Arctic have created tremendous social disruptions by conflicting with local communities and jeopardizing their environment. Existing legislation does not provide adequate reimbursement of damage inflicted to environment of indigenous groups. Oil and gas development causing massive environmental pollution has driven many indigenous people so desperate, that some of them are already prepared to defend their lands and traditions with arms in their hands (Greenpeace Russia, 2012b).

11.6 NATURAL GAS FLARING

Natural gas is deliberately burnt by the oil companies. The gas bubbles up alongside the far more valuable oil. Technically the gas can be captured and utilized. With less economic incentive to capture it, the drillers treat the gas as waste and simply burn it. The pollution from the flaring damages soil, water and air quality. The flaring of gas adds annually some 360 million tons of CO_2 emissions, equivalent to the annual emissions from about 70 million cars. The 140 billion m^3 of gas flared worldwide in 2011 (or 380 million m^3/day) is equivalent to almost 30% of the EU yearly natural gas consumption (World Bank EI, 2013). The energy content of this amount of gas is (for 10 kWh/m^3) corresponding to 1,400 TWh. Assuming 50% power plant efficiency this amount of gas can deliver all electrical power needed for Germany for more than 1 year, or 16% of the US electrical power consumption. The major source countries of flared natural gas are depicted in Figure 11.4.

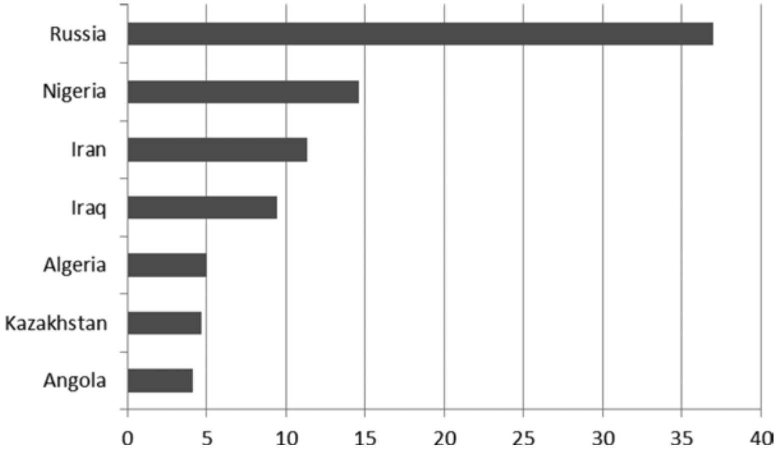


Figure 11.4 The largest source countries of flared natural gas in 2011 (in 10^9 m^3). The total global flaring is about 140 billion m^3. (*Source*: NOAA).

11.6.1 Nigeria

The World Bank reported in 2004 that 'Nigeria currently flares 75% of the gas it produces.' This means that about 70 billion m^3 of gas is wasted via flaring every year (or 190 million m^3/day). It is the equivalent to 40% of the entire African continent's gas consumption in 2001. Statistical data associated with gas flaring are notoriously unreliable, but the Nigerian Gas Association (NGA) has estimated that Nigeria has lost about US$ 72 billion in revenues (between US$ 500 million and 2.5 billion annually) in the period 1970–2006 period due to not selling, but burning the gas. The World Bank estimates (based on satellite data) that the gas flaring volume in Nigeria was reduced from 21.3 billion m^3 in 2005 (58 million m^3/day) to 15.2 billion m^3 in 2009 (42 million m^3/day) (World Bank EI, 2013).

Natural gas flaring is a huge waste of energy and has an enormous negative impact on the environment and people.

Companies operating in Nigeria also harvest natural gas for commercial purposes, but prefer to extract it from deposits where it is found in isolation as non-associated gas. Thus associated gas (see Glossary) is burned off to decrease costs. There are currently approximately 100 continuously burning gas flares in the Niger Delta and just offshore. Gas flaring in Nigeria began simultaneously with oil extraction in the 1960s by Shell. Nigeria produces more than 10% of global gas flares. Alternatives to flaring are gas re-injection, or to store it for use as an energy source. In Western Europe 99% of associated gas is used or re-injected into the ground. While flaring in western countries has been minimized it has grown in Nigeria proportionally with the oil production. It is estimated that the gas flaring accounts for about 50% of all industrial emissions in the nation and 30% of the total CO_2 emissions.

In November 2005 a judgment by the Federal High Court of Nigeria ordered that gas flaring must stop in a Niger Delta community as it violates guaranteed constitutional rights to life and dignity (www.climatelaw.org/media/2005Nov14/). In a case brought against SPDC, Justice C. V. Nwokorie ruled in Benin City (Edo State, Nigeria) that ‘the damaging and wasteful practice of flaring cannot lawfully continue.’ As of May 2011, Shell had not ceased gas flaring in Nigeria (www.irinnews.org/report/95034/). Data from 2011 show that companies on the Niger Delta have only reduced flaring 10% since 2007.

11.6.2 Gas flaring in other countries

The practice of gas flaring is still common in countries like Indonesia, Mexico, Iraq, Iran and Russia. Russia – the biggest gas flaring nation – flares about 3 times more gas than Nigeria, but produces 4.5 times more oil. Russia increased its flaring in 2011 by 1.8 billion m^3 to 37 billion m^3, a 5% increase.

However, it is quite remarkable that US producers are practicing exactly the same gas flaring. Wells in North Dakota’s Bakken shale, for example, produce gas in addition to oil. At present (2014) the site doesn’t have enough pipeline capacity to use all the gas extracted so workers burn off significant quantities of it. Actually the US increased the amount it flared by nearly 50% in 2010–2011. In the last five years the flaring has increased a factor of 3. Flaring is clearly undesirable in terms of air pollution and greenhouse gas production and is a waste of a natural resource. Every day more than 2.8 million m^3 of natural gas is flared this way – enough energy to heat half a million homes for a day – or 30% of all natural gas produced in North Dakota (Turcotte *et al.* 2014). The flared gas emits more than 2 million tons of CO_2 per year, comparable to a medium-size coal-fired power plant. Gas flaring is also used in the Eagle Ford shale field in Texas. Oil producers on the North Slope in Alaska must re-inject gas that cannot be used. Ongoing efforts may lead to a federal requirement for reinjection in North Dakota and other localities (Turcotte *et al.* 2014).

11.6.3 Environmental impact

Gas flaring contributes to climate change. It also releases toxic components into the atmosphere with potentially harmful effects on the health and livelihood of the communities in the vicinity. A variety of poisonous chemicals are discharged, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), methanol (CH_3OH), carbon black (a material produced by the incomplete combustion of heavy petroleum products), volatile organic compounds (VOC) like benzene, toluene, xylene, and hydrogen sulfide (H_2S), as well as carcinogens like benzapyrene and dioxin (heterocyclic 6-ring where two C atoms are replaced by oxygen atoms, $C_4H_4O_2$).

Humans exposed to such substances can suffer from a variety of respiratory problems. The chemicals can aggravate asthma, cause breathing difficulties and pain, as well as chronic bronchitis. Benzene, known to be emitted from gas flares in undocumented quantities, is well recognized as a cause for leukemia and other blood-related diseases. Almost no vegetation can grow in the area directly surrounding the flare due to the prevailing heat.

As noted, flaring is a problem not only in the developing world but also in so called developed nations. The oil companies argue that they cannot afford to pay to capture the gas. So, instead the local citizens and the next generation have to pay the price. This is nothing less than a ruthless damage of our environment. One may argue that flaring is better than venting the gas directly into the atmosphere. Pure natural gas is mostly methane, which has a very high global warming potential. Still, the environment will pay for the economic greed.

11.6.4 Reducing gas flaring

The World Bank has challenged oil producers from around the world, companies and countries, to cut flaring by 30% during 2012–2017, reducing the annual flaring from 140 to 100 billion m^3 by the end of 2017 (World Bank EI, 2013).

The Global Gas Flaring Reduction Partnership (GGFR) brings together representatives primarily from major oil-producing countries and companies to reduce gas flaring. GGFR is also making efforts to utilize the associated gas for power generation. GGFR began its Phase 4 in 2013 and will now focus on key anchor countries – Indonesia, Mexico, Nigeria, Iraq and Russia – and on activities in their surrounding regions.

Satellite data on global gas flaring, which is a joint effort between GGFR and NOAA, show that overall efforts to reduce gas flaring are paying off. Flaring of gas associated with oil production has dropped worldwide from 172 billion m^3 in 2005 to 140 billion m^3 2011, a 20% reduction, according to latest satellite estimates (World Bank EI, 2013). Satellite monitoring has also confirmed a 15% drop in gas flaring intensity (ratio of gas flared to oil production volumes) since 2002. Gas flaring reductions since 2005 have cut greenhouse gas emissions by some 270 million tons of CO_2 emissions equivalent. Overall, Russia and Nigeria have seen the largest reductions, and there has also been progress in Algeria, Mexico and Qatar. Latest data for 2011, however, also shows a 2 billion m^3 increase in flared gas over the previous year, which is a warning that efforts to reduce flaring need to be sustained and scaled up.

11.7 OIL SAND EXPLORATION

> *We knew it had to be sustainable but the industry said, 'Let's just keep our head down and do a good job.' I think the momentum on the environmental side overtook us.*
>
> Greg Stringham, vice-president of the Canadian Association of Petroleum Producers

As energy resources are stretched increasingly unconventional sources become attractive. One of these is oil sand. Canada has become a big energy player. Only a decade ago Canada's oil sands were little more than an afterthought in the energy world. Oil prices were just beginning to increase sufficiently high to make mining in the subarctic Northern Alberta economically viable. The Alberta oil sands represent one of the top two oil reserves in the world with some 27 billion m^3 of crude oil reserves, only after Saudi Arabia (Gosselin *et al.*

2010, Section 1.1). This assumes that only 10% of the volumes-in-place of 270 billion m^3 can be extracted. With technology development it is assumed that the crude oil potential can be increased. The annual investments in the oil sands operations have increased at a phenomenal rate, from Can$ 1 billion in 1996 to Can$ 16 billion in 2008. The Alberta Government has defined three Oil Sand Areas: Athabasca, Peace River and Cold Lake. Together they cover an area of 142,000 km^2, where Athabasca is the largest one. One of the large open-pit mines is located north of Fort McMurray.

11.7.1 Oil sand

Oil sand exploration requires at least three times more water than conventional crude oil exploration (Table 9.7). Compared with conventional and crude oil the bitumen (a dense form of petroleum) oil has a lower hydrogen-to-carbon ratio (about 0.125 weight/weight or 1.5 on atomic basis). Conventional oil has 2 H atoms for every C while methane has 4 H atoms for every C atom. The bitumen has also a higher content of sulfur, nitrogen and metals, such as nickel and vanadium. A typical ore in the Athabasca oil sands contains 8–14% (weight) of bitumen and 3–5% (weight) water (Gosselin *et al.* 2010, p. 32).

The oil sand consists of layers of sticky, tarlike bitumen mixed with sand, clay and water. In many deposits some 30 m of soil must be stripped off to reach the oil sand. Oil sand surface mining operates on extreme scales. The sand is delivered to an extraction plant where the bitumen is separated from sand in a hot-water wash, sometimes with caustic soda (NaOH, a highly corrosive, odourless white solid) to facilitate the separation of bitumen from solids. The bitumen rises to the top of the wash and the sticky load is sent to an upgrading facility that converts it to synthetic crude oil. Some 20% of the ultimately recoverable volume is considered economically recoverable using surface mining.

The biggest part of the recoverable oil is located deeper. When the bitumen is located too deep to be strip-mined, the industry melts it 'in situ' with copious amounts of steam, thus decreasing the bitumen viscosity, so that it can be pumped to the surface. Actually 80% of the potentially recoverable bitumen is in deposits deeper than 60 m (Wu *et al.* 2009).

Sand, water and bitumen residues are finally piped to a pond where the water is extracted, cleaned and reused in the mines. Actually, the 'pond' is rather a lake of toxic mine tailings that serves as a settling basin. The area of a dam can be about 10 km^2. The current tailing ponds in operation occupy an area of 176 km^2 and a volume of more than 720 million m^3. Thus the average depth of tailing ponds is 5.5 m (ERCB, 2010). It is noted that the volume of tailing ponds will increase with an alarming rate with current size of operations (Gosselin *et al.* 2010, p. 39). Within an area of about 3000 km^2 there are six mines that produce around 120,000 m^3 a day of synthetic crude oil. To get 1 m^3 of synthetic crude oil requires around 11 tons of oil sand at 90% recovery. It should also be emphasized that any loss of containment structure might lead to a catastrophic disaster.

The waste usually consists of 50–60% water, which makes the transport and storage quite demanding. For a typical plant producing some 48,000 m^3/day of bitumen around 250,000 m^3/day of oil sand ore is processed, producing around 1 million m^3 of raw tailings. It also produces around 1,800 m^3/day of sulfur and 300 m^3/day fly ash (Majid-Sparks, 1999). Some 75–85% of the water is typically recycled from the tailing ponds, even if some company (BP, 2014b) assert that they aim for a 90% recycle after 2014.

Estimates of the bitumen production were 208,000 m^3/day in 2008 and are predicted to exceed 450,000 m^3/day in 2018 (Gosselin *et al.* 2010, Table 2.1). There are some variations in estimates from different sources. The Athabasca crude oil production is predicted to increase to at least 150,000 m^3/day in 2018 (Gosselin *et al.* 2010, Table 2.2).

11.7.2 Water and energy use in the exploration

The exploration and processing of oil from tar sand requires not only huge volumes of water but also significant amounts of energy.

Water

Both mining and in situ operations use large volumes of water for extracting bitumen from the oil sands. The water is primarily withdrawn from the Athabasca River, but also from other sources, such as groundwater. The Canadian National Energy Board (NEB) has calculated that to produce 1 m^3 of synthetic crude oil some 2–4.5 m^3 of water is needed (NEB, 2006, p. 38). On a daily basis the mining projects are licensed to withdraw 1 million m^3/day (or 11 m^3/s) from the River. The expansion of the operations pushes the withdrawal to 1.45 million m^3/day (or 16.8 m^3/s). The historical low flow of Athabasca River is around 100 m^3/s. (As a comparison Bailonggang Wastewater Treatment Plant, Shanghai, the largest treatment plant in Asia, has a capacity of 23 m^3/s, while Stickney Water Reclamation Plant, Chicago, the world's largest, has a capacity of 63 m^3/second. These plants are municipal, with parts of the load from industries. The mining tailing ponds contain industrial waste that requires refined technologies for treatment.) The Athabasca River does not have sufficient flows to support the needs of all planned oil sands mining operations and at the same time ensure the ecological sustainability. In particular, during the winter the river flows are lower (NEB, 2006).

There is no corresponding regulation to limit the groundwater use. The pollution of groundwater has a much longer duration compared to river water. The flow velocity in the river is of the order meters/s while the velocity of the groundwater is meters/year. Thus, the influence of contaminants will last much longer in groundwater. Since in situ mining involves both groundwater extraction and steam injection in the subsurface, the issue of groundwater contamination is of primary interest. There is lack of information of these processes. Also the drilling process for the in situ operations involves large risks for groundwater contamination if the casing is not properly done (compare the shale gas, Ch. 11.2). Furthermore, the steam injection will raise the groundwater temperature in the neighboring area. This in turn will increase the solubility of chemicals in the water.

The tailing fluid contains 70–80% water, 20–30% solids (sand, silt and clays) and 1–3% bitumen (Allen, 2008). Even if a majority of the clarified water is recycled from the tailing ponds, almost all of the water withdrawn for oil sands operations ends up in tailings ponds. The wastewater from the processing is warm, so from an energy point of view it is important to recycle the water quickly and not let it stay to cool in the tailing ponds.

The huge mining tailings ('ponds') can leach hydrocarbons, heavy metals, arsenic, selenium and other hazardous materials into surrounding waterways. Very little data has been found of the fate of the wastewater contaminants on the impoundment structures but some studies are reported by Gosselin *et al.* (2010), Section 8.2.2.

It is estimated that surface mining operations require 2–3 liters of water per liter of bitumen while in situ operations require less, around 0.5 liter per liter of bitumen. Then 12–30 liters of water is used for every liter of oil (NEB, 2006; Gosselin *et al.* 2010, Table 4.1). Altogether, the production of crude oil from oil sands requires 100 million m^3 of water annually, or just above 3 m^3/s average flow rate.

Energy

It takes a lot of energy to extract the synthetic crude oil. The in situ extraction using steam can use up to twice as much energy as strip mining. Every day more than one million tons of sand emerges from the mining and is mixed with more than 200,000 m^3 of water that must be heated to between 45°C and 80°C to wash out the bitumen. This is done to decrease the viscosity of the bitumen. A temperature increase from room temperature to 50°C will decrease the viscosity 100 times. To reduce the operating temperature is highly motivated, since every degree reduction means a lot of energy. At the so called upgraders the bitumen gets heated again to about 500°C and compressed to more than 100 bar (10 MPa) in order to crack the complex molecules into the light hydrocarbons that we use in our cars. This synthetic crude is then transported to conventional refineries for a final transformation into fuels.

Most of the energy to heat the water or make steam comes from burning natural gas, which is the cleanest burning fossil fuel. Critics say that the oil sand industry is wasting the cleanest fuel to make the dirtiest. The Canadian National Energy Board estimates that 1 Mcf (1000 cubic feet) of natural gas per barrel of synthetic crude oil (for heating and electricity) is needed (NEB, 2006, p. 3). Expressed in metric units: for every m^3 of oil around 178 m^3 of natural gas is needed. The energy content of 1 Mcf is about 106 BTU which corresponds to 1050 MJ (see App. 1). Considering the energy content of crude oil (see App. 2) this means that for every 100 MJ of oil produced around 18 MJ of natural gas has to be used. Actually the oil sands production uses enough natural gas daily to heat more than 3 million homes. In total the production of oil from oil sand in 2010 required 0.6 Tcf (trillion – 10^{12} – cubic feet) or $28 \cdot 10^9$ m^3, which was more than 10% of all natural gas production in Canada (Gosselin *et al.* 2010).

Not only the bitumen processing but also the transportation of bitumen takes a lot of energy. In the plant producing 48,000 m^3/day of bitumen more than 500,000 tons/day of ore is transported in huge 150 ton trucks. The energy to move these trucks and their loads is about the same as to move the ore from the mine site to the processing plant (Gosselin *et al.* 2010, p. 41). In some operations slurry hydrotransport facilities are used, specially developed for oil sand extraction. They can reduce the energy need by 40% (Gosselin *et al.* 2010, p. 37). Slurry hydro-transport systems are being developed to remove some of the sand at the mining site, thus further reducing the energy consumption.

Obviously the oil sand operations generate a lot of greenhouse gas. The oil sands operations are the second largest CO_2 emitter in Alberta, so reducing the GHG emission is of national interest. Based on 2008 data the GHG emission of the oil sand operations is almost 6% of Canada's total GHG generation (Environment Canada, 2009). As a comparison fossil fuel power plants contribute with 16% and transportation with 27%, based on 2008 data.

11.7.3 Environmental concerns

Here we consider the environmental issues related to water and air and pay only little attention to public health and ecological consequences.

Water quality

The water quality and the ecological consequences for the lower Athabasca River and its tributaries are not well known but monitoring programs are being executed. Still there is a considerable uncertainty in the assessment of the water quality responses.

Polycyclic Aromatic Compounds (PACs) levels in river water of the Athabasca River, upstream and downstream of the bitumen upgrading facilities were studied by Kelly *et al.* (2009). PACs are organic compounds found in coal, crude oil and bitumen. The authors also monitored PAC levels in the snowpack due to the deposition of the airborne pollutants over the winter months. The researchers found increased levels of dissolved PACs in tributaries to the Athabasca River downstream of oil sands development and increased deposition of particulates and PACs in the snowpack close to the major bitumen upgrading facilities. The particulates sampled in the snowpack contained various PACs affiliated with oil sands development. This pollution may have a harmful effect on the fish in the River. That research drew criticism from the Government of Alberta and others for failing to provide a historical baseline.

Historical data could be provided in a later study from 2013 at Queens University, Kingston, Ontario (www.queensu.ca/news/print/37963). Layers of the sediment were tested for deposits of polycyclic aromatic hydrocarbons (PAHs). The PAHs are groups of chemicals associated with oil that in many cases have been found to cause cancer in humans after long-term exposure. The researchers found that the levels of PAHs deposits have been steadily rising since large-scale oil sands production began in 1978. Samples from one test site now show 2.5 to 23 times more PAHs in current sediment than in layers dating back to around 1960. Upgraders at some oil sands projects that separate the oil bitumen from its surrounding sand are believed to emit PAHs. Some scientists believe that vast ponds holding wastewater from that upgrading and from other oil sand processes may be leaking PAHs and other chemicals into downstream bodies of water.

Air quality

There are many sources of air pollution from oil sand operations, such as mining, extraction, upgrading, in situ recovery, and waste management. Combustion and upgrading sources emit via stacks and heavy equipment emits a lot of combustion emissions. Volatile organic compounds (VOC), benzene and odorous emissions from a mixture called total reduced sulfur (TRS), including hydrogen sulfide (H_2S) and several other sulfides (Kindzierski *et al.* 2009). These components will also arise from tailing pond evaporation and fugitive emissions wherever hydrocarbons are being handled. There are reasons for concern for the air quality in the region, according to data from the Clean Air Strategic Alliance (CASA) website www.casadata.org.

To put the emission of the toxic emission components in perspective, the oil sand industry is not at all the largest industrial emitter in Canada (2008), but would have to increase the emissions 5 times in order to become the largest emitter of any of the four major toxic components (Gosselin *et al.* 2010, p. 290). Still, there are odor problems that have to be resolved.

Surface water is vulnerable to acidification due to atmospheric deposition due to SO_2 and NO_x. It has been found that some 60% of the lakes in the region are highly or moderately sensitive to acidification (Gosselin *et al.* 2010, p. 152).

Observed pollutant depositions in the Athabasca oil sands region (Kelly *et al.* 2009) have been linked to sources using air dispersion modelling (MacDonald, 2013). The modelling work could illustrate that airborne particulate matter (containing toxic PACs) from oil sands upgrading plants are a source of pollutant deposition in the Athabasca oil sands region.

Pipeline constructions

Battles are under way over the proposed construction of the Keystone XL pipeline, which would move the oil down through the Western US and down to refineries along the Gulf Coast. In April 2014 the Obama administration announced that the review of the Keystone XL oil pipeline has been extended indefinitely, pending the result of a legal challenge to a Nebraska pipeline siting law that could change the route. The challenge has been taken up by the State Supreme Court. A bill to move forward with construction of the pipeline was approved by US Congress in February 2015 but vetoed by President Obama.

An alternative pipeline, called the Northern Gateway that would transport the oil from landlocked Alberta to British Columbia for export to Asia is proposed. The pipeline would transport oil almost 1200 km westwards. It is expected that more than 200 tankers per year – each one with more than 300,000 m^3 – would navigate between a jigsaw of islands to and from Kitimat in the inner part of a narrow fjord. Remember Exxon Valdez? The risk assessment in Alaska was quite optimistic.

11.7.4 The EU Fuel Quality Directive and oil sands

Is the oil from bitumen 'dirty oil'? In 2009, the EU announced the Fuel Quality Directive (FQD), Directive 98/70/EC] (http://ec.europa.eu/environment/air/transport/fuel.htm) which requires a 10% reduction from 2010 to 2020 in the GHG gas intensity of all the petrol, diesel and biofuels used for transport. The measure is part of the EU's current suite of climate and energy targets, which create an emissions reduction pathway up until 2020. The directive has existed for nearly 5 years and is used to calculate biofuels' *overall* emissions. It has never been used to regulate fossil fuels. That is because member states can't agree on a methodology for calculating lifecycle emissions. It has been suggested that Canada sees the Directive as a threat to its plans to export fuels derived from oil sands to new markets like Europe. Canada claims the Directive unfairly discriminates against unconventional fuels and overstates their impact on the environment and wants to stop the EU from declaring that oil sands have a higher carbon footprint. A great lobbying effort was in place in Europe, including many high level visits in Brussels.

Finally, in 2011, the Commission put forward a proposal that would set 'default' values for the amount of pollution that more polluting methods of production will produce. It would also require oil companies to report the carbon footprint of all their fuels. In proposed EU legislation, oil from oil sands was given a GHG value of 107 grams of carbon per MJ of energy produced, compared with conventional crude's allocation of 87.5 grams. In other words: burning oil from oil sands in the car – rather than conventional oil – makes the driver, overall, responsible for about 22% more CO_2 emissions. At a trade meeting in October 2013, both the US and Canada trade representatives allegedly warned the EU that the classifications in the Directive could count as a restraint of trade, punishable by world trade rules and a potential barrier to new trade agreements. Even the EU countries Poland and Estonia, having large deposits of shale oil are opposing the proposal. The same is true for Germany, UK (home for BP) and The Netherlands (home for Shell). Both the oil giants have large investments in the Canadian oil sand. While the EU is still hammering out the details of how the Directive will be enforced until 2020, it runs the risk of disappearing completely after that date. In January 2014 the EU provisionally decided to drop the FQD from its most recent set of climate targets, which will be in force from 2020 to 2030. If leaders eventually agree on a global cost for CO_2 emissions it could make extracting oil from sand simply uneconomic.

11.8 COAL

Globally we consume more than 3 kg of coal per person , every day

A few years ago I was invited to the Shanxi province (Map 3.1) and arrived to its capital Taiyuan, about 400 km southwest of Beijing. The primary reason was actually touristic. Close to Taiyuan there are several fantastic attractions, like the city of Pingyao that was China's 'Wall Street' between 1823 and 1923 and the spectacular 'hanging temple' Xuankong Si in northern Shanxi.

Shanxi produces some 70% of China's coal. It is also one of the driest parts of the country. In the Shanxi province, studies estimate that 1.07 m^3 of groundwater is polluted per ton of coal extracted. Smog and smoke dominates the sky of Taiyuan and the sun had a very special colour due to the air pollution. Taiyuan is not dry and the River Fenhe, tributary of the Yellow River, flows through the city. However, the river has dried up because of heavy abstraction to the coal mines. The city now relies mostly on groundwater abstraction.

Having spent almost a month every year for the last eight years in Beijing I have also got an immediate and personal experience what coal leads to in terms of air quality. Coal is the biggest contributor to both urban smog and climate change. It is the dirtiest (and cheapest) of the fossil fuels and provides about 40% of the world's electrical power and produces some 39% of global CO_2 emissions. Coal is also used in the production of 70% of the world's steel.

Coal causes around 39% of global CO_2 emissions

Coal mining has an enormous impact on both land use and on surrounding water quality. Mining and refining coal (refining includes washing and beneficiation) requires water at various stages (Tables 9.6, 9.7). Estimates show that approximately 0.16 liters of water is needed per MJ or 4 liters of water per kg of coal (Table 9.7).

11.8.1 The world coal resources

The world has of the order 10^{12} tons of readily available coal. Figure 11.5 shows the five countries with the biggest coal reserves. Together they have 75% of the world's known coal resources and the US has the largest share. There are two internationally recognized sources for assessing world coal reserves. The German Federal Institute for Geosciences and Natural Resources (BGR) estimates that there are 1038 billion tons of coal reserves left, equivalent to 132 years of global coal output in 2012. The World Energy Council (WEC) has a lower estimate, 861 billion tons, equivalent to 109 years of coal output.

The readily available coal reserves can last for considerably longer than 100 years with the current consumption rates.

More than 60% of the coal consumed was used to generate electric power in 2012. The global coal consumption (2012) is roughly $7.8 \cdot 10^9$ tons per year and China is burning the most as shown in Figure 11.6. Western Europe has actually cut the coal use by 36% since 1990 by using available natural gas from the North Sea and from Russia. As the world's largest energy user and CO_2 emitter, China currently uses almost 45% of the world's coal. A staggering 82% of the global increase in coal use since 2000 has been attributable to China, according to EIA (2014). The coal demand growth in China is the result of a more than 200% increase in Chinese electric generation since 2000, fueled primarily by coal. Of all fossil fuels, coal puts out the most CO_2 per unit of energy, so burning more coal poses a further threat to the global climate. There is an on-going effort to refine the technology of coal gasification, but this is outside the scope of this book.

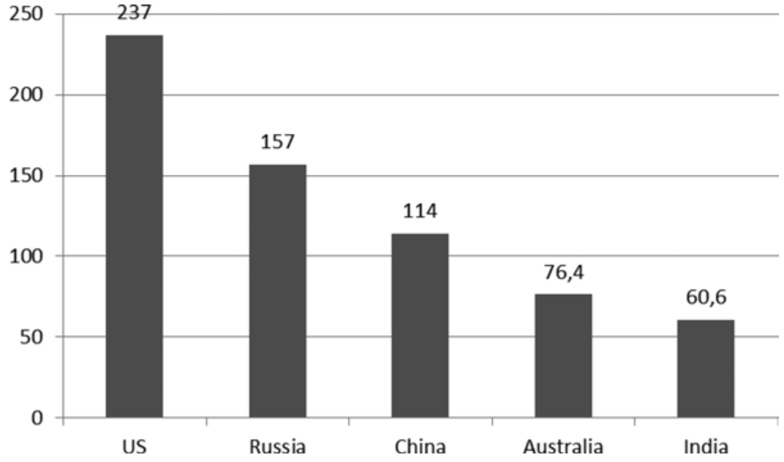


Figure 11.5 The global distribution of coal resources in Bt (billion tons). *Source*: www.mining-technology.com (August 2014).

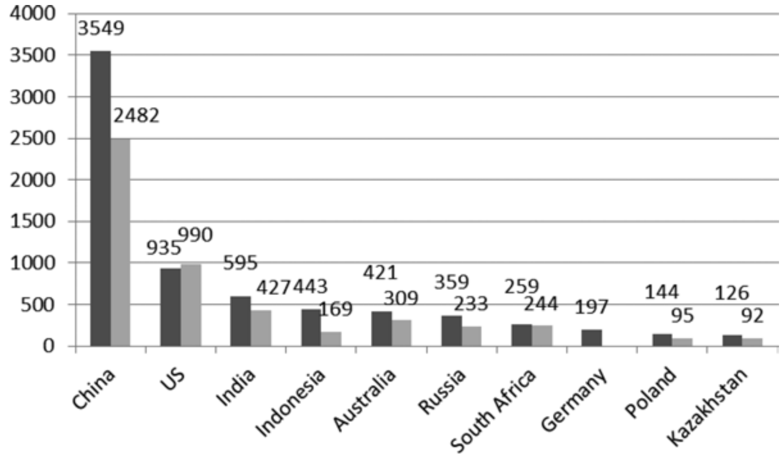


Figure 11.6 The top ten coal producers in Mt (millions of tons) per year. The left bars (black) are from 2012 and the right ones (grey) are from 2006. Most of the coal is 'hard' coal'. Germany is the biggest brown coal producer with 185 Mt/year. No data for 2006 is given. (*Source*: World Coal Association 2014, based on data published by IEA and BP in 2013).

The total world coal production reached a record level of 7831 Mt in 2012, increasing by 2.9% compared to 2011. The top ten producers are shown in Figure 11.6. China and the US consume about close to 100% of their production, while the large coal exporting countries are Australia with around 300 Mt (69% of its production), Indonesia 290 Mt (85%) and Russia 90 Mt (28%) (Yang-Cui, 2012).

More than 60% of the coal consumption is for generating electrical power.

In comparison with 2006 the production has increased 43% in China, 39% in India, 36% in Australia. Indonesia has more than doubled its production, an increase by 162%. In the same period the US has decreased its coal production by 9%. With the rapid industrialization of China and India a lot of coal is burned to manufacture many of the West's consumer products. The coal use per capita gives another perspective. Comparing the average daily consumption of coal per person among the ten biggest coal consuming countries gives another comparison, Figure 11.7. Australia has the biggest consumption among in the group, five times the world average.

The global coal consumption will still rise by 1.1%/year until 2035 (BP energy outlook, 2014). The increase will take place in the non-OECD countries (1.6%/year) while there will be a decline in the OECD (–0.9%/year).

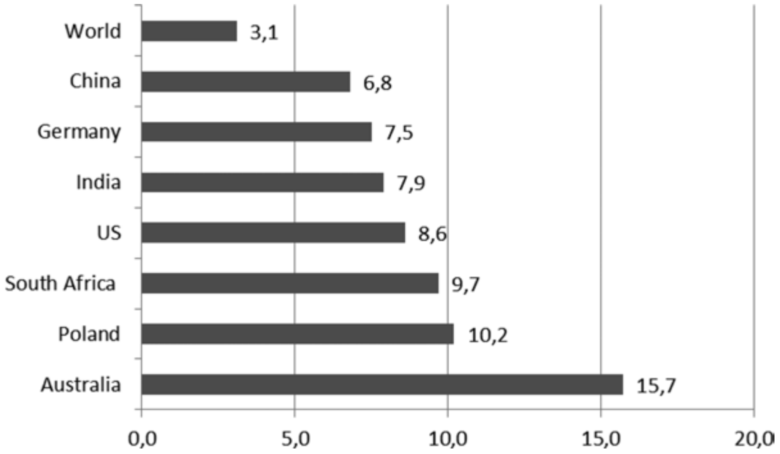


Figure 11.7 Average daily consumption (kg) of coal per person among the ten largest coal consuming countries. (*Sources*: Coal consumption WRI (2014); Population statistics: Wikipedia).

- China and India combined will contribute 87% of the global coal growth to 2035.
- China will remain the largest coal consumer in 2035 with more than half the global consumption. However, the growth of China's coal demand will decelerate rapidly from 6.1%/year in 2005–15 to just 0.1%/year in 2025–35. After 2030, demand will likely decline, driven by the rebalancing of China's economy toward services and domestic consumption, and supported by efficiency improvements and more stringent environmental policy. China's profile explains the marked slowdown in global coal growth.

- India will overtake the US to occupy second place in 2024. India's demand growth, in contrast, remains robust; rising from 5.9%/year in 2005–15 to 3.0%/year in 2025–35 as the country's industrialization continues. In the final decade India replaces China as the leading source of coal demand growth.
- The OECD's share will drop from 28% in 2012 to 18% in 2035.

It may be illustrative to consider the coal consumption to produce 1000 MW of electric power. Some 8 tons of coal has to be burned every minute, and this requires about 100 train cars of coal per day or some 12,000 tons.

To produce 1000 MW of electric power requires around 8 tons of coal every minute.

11.8.2 Coal consumption and the environment

Coal burning has a devastating consequence for air quality and public health, in particular emissions of local pollutants, particularly sulfur dioxide (SO_2), nitrogen oxides (NO_X) and particulates. China's coal consumption killed over 600,000 people in 2012 and counted for as much 60% of particles 2.5 micrometers or less in size (commonly known as PM 2.5) in China's air, according to a report released in November 2014 (Natural Resources Defence Council, NRDC (China Global Times 6 Nov 2014). The report is a co-operation between the NRDC, Chinese Academy for Environmental Planning under the Ministry for Environmental Protection, China's National Climate Center and China Coal Research Institute. An estimated 670,000 deaths in China in 2012 were caused by heavy coal usage and smog related diseases such as heart disease, stroke and lung cancer. The many premature deaths a year in China due to the air pollution is on top of the thousands who die in mining accidents, in China and elsewhere. These problems are not new. In the late 17th century the English writer John Evelyn complained about the 'stink and darknesse' of the smoke that wreathed London, heated by coal from Wales and Northumberland. In December 1952 London suffered particularly dangerous smog, provoking respiratory ailments that killed as many as 12,000 people in the following months.

The Chinese air pollution report claims that for each ton of coal consumed it also produced a US$ 42 worth of damage to the environment and human health, while the Government currently only charges some US$ 4.8–6.4 in environmental fees and taxes for each ton. This means according to the report that 'the country's current pricing system has failed to reflect the true costs behind coal consumption.' It is also stated that more than 70% of China's population lives in regions with high levels of PM2.5 (small enough to invade even the smallest airways).

The climate change will depend on what the world does with its coal, and in particular what the US, China and India will do. Scrubbers in coal-fired electric power plants can clean some of the sulfur and mercury – but not the CO_2 – from the smoke. Even the most aggressive push for alternative energy sources and conservation could not replace coal – at least not right away.

The efficiency of a coal-fired power plant is of fundamental importance. The global average efficiency of coal-fired power plants currently in operation is roughly 33%, much lower than for power plants that rely on other fossil fuel sources and significantly lower than the 45% efficiency possible with modern, ultra-supercritical coal-fired power plants. If coal-fired units currently in operation around the world could be upgraded to operate at an average of 42% efficiency, annual CO_2 emissions would fall significantly. In addition, higher efficiency coal-fired plants consume less fuel, and emit fewer local pollutants. More efficient units consume less water. While it is important to reduce water consumption through the whole coal chain, from mining to utilisation, improving both the efficiency and operation of generation units can have a significant impact. For these reasons, the International Energy Agency (IEA) and China's National Energy Administration (NEA) approached the China Electricity Council (CEC) to work with IEA to identify achievements possible through the upgrading and retrofitting of older coal-fired power plants. Two plants of 300 MWe were used as case studies (IEA, 2014b).

Water could become a serious constraint on the coal industry in arid countries like China and South Africa unless major improvements in energy and water efficiency are made. In China in 2011 the coal industry, from mining to power generation and coal-to-chemicals conversion, accounted for roughly one-sixth of China's water withdrawals. Most of the water withdrawals in China, 87%, is for coal-fired power generation. In South Africa, 93% of the electricity generated is coming from coal-fired stations. This implies a major environmental footprint. Water scarcity is a critical issue in South Africa. Two giant coal-fired power plants, Medupi and Kusile, are under construction and will use dry cooling technology (see Chapter 13). However, the water problems in coal mining to supply these plants with fuel, each one with 4800 MW_e capacity, will be huge. Between 65 and 80 tons of coal has to be produced – every minute. This has enormous impacts on water availability, water quality, and will have large social impacts (Greenpeace, 2012). Much of South Africa's coal is surface-mined poor quality coal, with high ash and sulfur content. The coal will therefore probably need some washing before being burned in the plant (Alstom, 2009).

11.8.3 Coal mining

An important consequence of coal mining is the so called acid rock drainage (ARD) or acid mine drainage (AMD). It is a result of the contact that is created between coal surfaces, air and water. The pyrite (iron sulfide, FeS_2), also known as 'fool's gold', then oxidizes to form ferrous sulfate and forms sulfuric acid (H_2SO_4). This acid will be mixed with drainage water from the coal mine. If sufficient alkalinity is available then the acid water produced by the AMD chemical reactions may persist for only a short time. Once the neutralization capacity is exceeded, however, acid begins to accumulate and the pH decreases. A stream will become polluted by pH shocks that will kill fish and plants, since most of them are sensitive to significant pH changes. Modeling predictions and comparison to a limited number of field sites indicate that the acid production peaks 5 to 10 years after mining, followed by a gradual decline over 20 to 40 years (Sams-Beer, 2000). Many discharges have a pH less than 3.0 and the water generally has high concentrations of acidity, iron, manganese, aluminum, and sulfate. Water quality is thus severely degraded as it enters streams and rivers. The costs to clean up the AMD problem from abandoned mine-land sites are substantial.

Another harmful product is methane. It has been absorbed by the coal deep in the ground and will be released during the mining process. The release of the gases is a result of the relaxation of the pressure and the fracturing of the strata during the mining process. The methane has a large global warming potential (Chapter 4). Burning coal in power plants will cause a deteriorated air quality, and the mining of coal can release pockets of hazardous gases. It is well known that these gases are a serious threat to coal miners.

New evidence of methane from coal mining has been found in the Four Corners region in the US (where Utah, Colorado, Arizona and New Mexico meet). Satellite data have revealed that the levels of methane concentration in an area of about 2,500 square miles (6,500 km^2) are three times the expected value (Kort *et al.* 2014). It is the largest concentration of methane gas seen across the nation. The zone is over New Mexico's San Juan Basin, home to thousands of wells that pull natural gas from coal beds. The area generated an annual 0.59 million metric tons of methane between 2003 and 2009. Since the measurements are recorded before 2009 any influence of shale gas and hydraulic fracturing can be excluded. The amount of methane is about as much as the entire coal, oil, and gas industries of the UK give off each year.

11.8.4 Surface mining

Surface mining is a most destructive way of coal mining. Not only does it change the appearance of the landscape but it also affects streambeds. Wherever it occurs in the world, it eliminates existing vegetation, destroys the genetic soil profile, displaces or destroys wildlife and habitat, degrades air quality, alters current land uses, and to some extent permanently changes the general topography of the area mined. Strip mining is one type of surface mining. A seam of mineral is mined by first removing a long strip of overlying soil and rock, called the overburden. It is used when the ore body to be excavated is relatively near the surface. Then the operator removes the horizontal contours of a mountain side. The ARD is serious in strip mining. Then the entire exposed seam leaches sulfuric acid.

During recent years coal mining has turned to an even more aggressive surface mining process known as mountaintop removal. Beneath mountaintops threaded by streams and blanketed by hardwood forests lie shallow coals seams. After clear-cutting a peak's forest, miners shatter its rock with high explosives. The rubble (overburden) is scooped and dumped in a nearby hole or valley. The method was tested in Kentucky and West Virginia in the US already in the 1970s, sparked by the petroleum crises in 1973 and 1979. Since then it has spread to Virginia and Tennessee. The results have been ecological disasters. The driving force for the mining is that mountain topping is less labour intensive than underground mining and is more efficient and profitable than the older form of surface mining.

To expose the coal seams, giant draglines remove the overburden of rock and dirt. If the coal needs to be washed to remove impurities, impoundments ponds store the resulting toxic sludge and wastewater. The threat of a collapsed impoundment or valley fill is a concern.

Once the coal is removed, coal companies are required (at least in the US) to restore the mining site to a 'level of gently rolling configuration'. This may include planting non-native grasses and scattered stands of quick-growing trees but also includes a prison in Kentucky and golf courses in other states. Naturally the animal life has been radically changed. However, putting the entire top of a topped-off mountain back together again was a more expensive matter, so some mountaintop mines were given a blanket exemption from this requirement.

The impoundment ponds – sometimes called slurry ponds, sludge lagoons or waste basins – often remain. Only in the Appalachian Mountains in the eastern USA there are more than 500 of these impoundments. In a number of tragic cases a flood of loose sludge has created a lot of damage. One example is the Buffalo Creek Flood in 1972. A coal slurry impoundment in Logan County, West Virginia burst four days after having been declared 'satisfactory' by a federal mine inspector. The resulting flood unleashed some 500,000 m^3 of wastewater.

125 people were killed and more than 4000 were left homeless. In its legal filings, Pittston Coal referred to the accident as 'an Act of God.' It is not God's fault – it is an act of ruthless and greedy energy exploration. Besides the danger to life and property, large amounts of sediment and poor quality water may have detrimental effects many miles downstream from a mine site after a flood. Overall, it will cause a lot of pollution in drinking water.

'Act of God' (according to a coal company) = neglect.

EPA has attempted to limit the practice of burying streams under excess rock while extracting coal. The coal industry has been challenging the EPA's water quality guidelines for Appalachian mining operations. A federal judge has now ruled that EPA exceeded its statutory authority under the Clean Water Act (Water 21 Global News Digest, 18 Nov 2011). The judge has now re-established the US Army Corps of Engineers as the primary permitting authority.

Open cut coal mining requires large amounts of water for the operation of coal washing processes as well as the suppression of dust. Water requirements for coal preparation vary depending on the condition of the coal coming out of the mine and the washing requirements of the power plant. It is estimated by the Department Energy (DOE, 2006, p. 55) that between 75 and 150 liters of water is used to wash 1 ton of coal. This corresponds to roughly 13–33 liters of water per MWh of electricity produced. As a result the agricultural and domestic needs are often sacrificed. These water resources are rarely returned after the mining operations have closed and will create a permanent degradation to agricultural productivity. Underground mining has a similar but lesser effect due to a much lower need for dust suppression water but still requires sufficient water to operate washing processes.

Washing coal creates water contaminated with heavy metals and other pollutants, and if improperly managed, this 'produced water' can end up seeping into groundwater or draining into rivers and lakes where it can devastate wildlife, pose health risks for neighboring communities and degrade recreational areas. On average, water *withdrawals* for coal mining, washing and processing amount to approximately 220 liters/MWh of electricity produced.

11.9 FOSSIL FUELS, SUBSIDIES AND THE CLIMATE

Governments across the G20 countries are estimated to be spending US$88 billion every year subsidising *exploration* for fossil fuels (Bast *et al.* 2014). The evidence points to a publicly financed bail out for carbon-intensive companies, and support for uneconomic investments that could drive the planet far beyond the 2°C climate change. The report discovers that the G20 Governments' exploration subsidies combine bad economics with potentially disastrous consequences for climate change. Actually, governments are propping up the development of oil, gas and coal reserves that cannot be exploited if the world is to avoid dangerous climate change. The G20 countries are in fact creating a 'triple-lose' scenario as a result of the subsidies. Large financial resources are directed into high-carbon assets that cannot be exploited without catastrophic climate effects. Investments are also diverted from economic low-carbon alternatives such as solar, wind and hydro-power.

In 2009, according to Bast *et al.* (2014), leaders of the G20 countries pledged to phase out 'inefficient' fossil-fuel subsidies. The Bast report shows that there is a large gap between G20 commitment and action. Table 11.4 shows how the subsidies are directed.

Table 11.4 G20 country subsidies for fossil fuel exploration.

Type of subsidy	Billion US$
Investments by state-owned enterprises	49
National subsidies (direct spending and tax breaks)	23
Public finance (from banks and financial institutions)	16
Total G20 government support	88
Private company investment by the top 20 global oil and gas producers	37
National subsidies for fossil fuel exploration:	
US (2.6 billion in 2009)	5.1
Australia	3.5
Russia[1]	2.4
China[1]	1.5
UK	1.2

[1] In addition to the investment and finance provided by their majority state-owned enterprises and state-owned banks.
Source: Bast *et al.* (2014).

IEA estimates that the fossil fuel subsidies of US$88 billion are twice as much as would be needed to achieve universal access to energy by 2030. It is also more than double the global spending on exploration by the top 20 private oil and gas companies. This suggests that their exploration is highly dependent on public finance.

The global subsidies for the production and use of fossil fuels is an order magnitude large than the support for exploration. In 2012 this global support were estimated to US$775 billion. Then the costs associated with air pollution and greenhouse gas emissions are not taken into account. Subsidies for renewable energy amounted to just $101 billion in 2013.

Global subsidies for fossil fuels are almost US$ 900 billion while subsidies for renewable energy amount to around $100 billion.

The subsidies encourage fossil fuel exploration and create incentives for oil and gas companies to continue to find new oil, gas, and coal reserves. As noted in 4.3 IEA warns that *only one-third* of the proved reserves of fossil fuels should be used by 2050 if we are to meet the climate goals. Already now the proven reserves are three times the amount that can be safely burned. Obviously the oil and gas companies have no incentive to turn into renewables.

Bast *et al*. (2014) compares the subsidies to the real investments. For every US$ in renewable subsidies there were US$2.5 invested. For every US$ subsidizing fossil fuels only US$1.3 were invested. The transparency of the fossil fuel subsidies is not impressive. How can citizens and legislative bodies become aware of the spending on fossil fuels?

Can this explain the lack of real progress in the climate negotiations?

A common argument to justify the continued subsidies for fossil fuel is to provide energy for the poorest, the 20% of the world population without access to electricity and the 40% without access to modern fuels for heating and cooking (see 9.2). The World Coal Association recently released a report claiming that coal has a ‘vital role’ in ‘delivering energy to the 1.3

billion people who lack access to it as well as coal's role in building sustainable communities' (Bast *et al.* 2014). However, universal energy access is not achieved by centralized fossil fuel projects. A majority, some 84%, of the people who lack access to electricity live in rural areas, often far away from the electric power grids. Distributed electrical energy systems rather than the centralized system are needed. The IEA has estimated that around 2/3 of the investments to achieve universal energy access, would need to be in distributed energy – mini-grid and off-grid options that most often rely on renewable energy sources.

The coal production and consumption in two countries, the US and China, will to a large extent determine what happens on a global scale with the climate change, caused by burning fossil fuels. The climate is going to be profoundly affected by increasing electric coal power generation. The World Resources Institute (Yang-Cui, 2012) has identified the plans or proposals for 1200 new coal-fired plants (July 2012) globally, with a total installed capacity of 1400 GW_e. This can be compared with the total coal fired power plant capacity of 1700 GW_e, producing over 41% of the world's electricity (IEA, 2014b). These projects are spread across 59 countries. China and India together account for 76% of the proposed new coal power capacities. The list of plants does not take into consideration whether the project is officially seeking approval, what the timeline of the project construction is or the likelihood of the project being built eventually. Many of the plants are planned to be located in arid regions. For example, the 12th Five-Year-Plan in China approved 16 giant coal-power bases, mainly in the northern and northwestern provinces of Inner Mongolia, Xinjiang, Shanxi, and Shaanxi (Yang-Cui, 2012). Most of the proposed projects are located near coal mining fields but have apparent water scarcity problems. Let us consider the two largest coal consumers, US and China.

Coal-fired power plants produce over 41% of the world's electricity.

11.9.1 US

In June 2014 the Obama administration announced curbs on CO_2 emissions from the nation's 600 coal-fired power plants with the aim to deliver a cut in US carbon emissions from power plants of 30% between 2005 and 2030 (United States CAR, 2014). The Environmental Protection Agency (EPA) estimates that the measures, combined with the growth of shale gas, will take coal's share of US electrical power production from more than 50% in the late 1990s to 31% by 2030. Hundreds of coal-fired power plants are expected to close under the EPA plan. As alternatives to shutting down plants, states would be allowed to reduce emissions by making changes across their electricity systems – by installing new wind and solar generation or energy-efficiency technology, expand the use of natural gas, and by starting or joining state and regional 'cap and trade' programs.

The proposed regulations could be held up by legal and political battles. The EPA will issue its final guidelines by June 2015. The states will have until June 2016 to file their plans to meet the guidelines, with possible two-year extensions. The EPA will then decide which of the plans are adequate. President Obama will leave office in January 2017, so most of this process is likely to play out under his successor.

11.9.2 China

Within hours of the US administration's announcement in June 2014, there were renewed hints that China, as the world's largest coal user, is headed in the same direction. This would be a remarkable turnaround. The rise in the past decade of coal, the most carbon-intensive of major fossil fuels, has been astounding. For all the political talk of cutting carbon emissions, coal's share of global energy rose from 25 to 30%. Most of this was due to China, which gets 80% (Pearce, 2014). There will be a peak of coal consumption, followed by a long decline, according to BP Energy Outlook (2014), which suggests that between now and 2035, 'coal's contribution to growth (in China) diminishes rapidly,' with renewables being the biggest winner. The growth in China's energy demand is waning because GDP growth is slowing. The reason is that the GDP growth will be based less on industrial activity and more on the services economy, Also, China is making big strides in using its energy more efficiently. More than 17,000 industrial and other enterprises currently have mandatory targets for improved energy efficiency.

Concern about smog is now a major political issue in China. The regular TV footage of near-zero visibility in major cities has been backed up by recent research findings that dirty air is cutting more than five years off the life expectancy of the half-billion citizens of Northern China.

In the search for alternatives, China is now the world's biggest investor in renewables. It spent \$56 billion in 2013 alone. That has made China the world's largest generator of both solar and wind energy. Along with hydro-dams, solar and wind now deliver 9% of China's electricity. Meanwhile, shale gas is on the horizon (see 11.2), and some 40% of the nuclear power plants currently under construction in the world are in China, where 28 nuclear plants are under construction.

A final reason why China is on course to reduce its dependence on coal is its climate policy. China already has rules to curb its soaring carbon emissions. So far, these relate only to reducing the carbon intensity of its economy, which is defined as the number of tons of carbon emitted per dollar of GDP. China is committed to reducing carbon intensity by 40–45% from 2005 to 2020. In 2012, the economy grew 8% but emissions grew only 3%.

Since China burns half the world's coal, this matters hugely for the planet. An early peak and sharp decline in China's coal burning would almost certainly trigger massive changes to the global coal industry. What is of vital importance is also that other developing countries will follow China. India, the other coal superpower, is increasingly beset by smog, since the coal industry provides 70% of the country's electricity. But there are signs that India could be ripe for change too. Probably the smart investment would be in new renewables, wind and photovoltaics.

11.10 CHAPTER SUMMARY

Our climate will be determined what we do with the fossil fuels. It is increasingly obvious that fossil fuel exploration and refining also have a large water footprint. Large water quantities are needed for oil exploration, hydraulic fracturing, oil sand and coal exploration and this is a critical issue in dry areas. The 'produced' water is most often seriously contaminated and few reliable treatment methods have been developed or used. Many chemicals used in fracking fluid or produced water from exploration have increasingly been found to be harmful both to the environment and to human health. Yet poor regulations, corruption and legislation often allow accidents which contaminate surrounding water sources. Any fossil fuel exploration should have to report:

- water demand;
- treatment result of produced water;

- environmental assessment of the fossil fuel operations;
- improper disposal of wastewater;
- community and social disruption due to operational activities.

The need for more transparent rules for extraction is obvious. There is a tragic series of accidents related to oil spills, coal mining, and natural gas flaring. Many of these spills are a result of poor maintenance, insufficient safety rules, too little regulatory monitoring, or simple ruthlessness. The enormous economic interests have influenced corrupt decision makers, affected safety culture, and caused disastrous environmental damage and terrible human suffering in too many places.

We will have to deal with fossil fuels for many decades ahead. Investments in crude oil, shale oil, oil sand and coal are also likely to delay needed global investments in new renewable energy, such as solar photovoltaics and wind. It is crucial that policy makers and decision makers should understand the full spectrum of risks. Strict international, national and local regulations are required, but also a strict monitoring from regulatory agencies. To gain the confidence of the public the process has to be transparent and has to allow all voices to be heard.

11.11 RECOMMENDED READING AND VIEWING

The recent UN World Water Development Report 2014 (UN WWDR, 2014) presents an excellent overview of the water and energy. In particular, Chapters 3 and 9.2 describe the energy's thirst for water.

Oil exploration: Youtube (www.youtube.com) can provide a lot of illustrations of oil exploration. Search for 'oil exploration'. A report on shale gas, aimed for policy makers, has been published recently (Hoffman *et al.* 2014). The World Resources Institute has published a global and country-specific analysis to help evaluate freshwater availability across shale resources worldwide (WRI, 2014). The book by Zuckerman (2013) is a fascinating story about the 'frackers'. Voinov-Cardwell (2009) report water consumption data for oil refineries.

Gas flaring: A view of global gas flaring based on satellite observations can be seen on Youtube (https://www.youtube.com/watch?v=miOJ86B4xe8). It is a joint effort between the US National Oceanic and Atmospheric Administration (NOAA) and the World Bank-led Global Gas Flaring Reduction partnership (GGFR). The video is from 2009.

Oil spills and accidents: The Deepwater Horizon accident has been widely published and a detailed description of the accident and its consequences can be found in Wikipedia. There are numerous videos describing the spill, easily found on www.youtube.com (search 'Deepwater horizon'). The Gulf Oil Spill is also described in Bourne (2010). Health related problems after the Gulf oil spill are reported in McCoy-Salerno (2010).

A detailed account of the Exxon Valdez accident is found in National Geographic, first by Hodgson-Fobes (1990) and then ten years after the accident by Mitchell (1999). The book by Wells *et al.* (1995) gives a detailed description of the disaster and Peterson *et al.* (2003) describe the long term ecosystem response to the oil spill.

An exhaustive assessment of the Niger Delta oil spills is given in the UN report UNEP (2011b). The cited reports from Amnesty International (2009), Amnesty International and CEHRD (2011, 2013) present the oil tragedies from both technical and human rights perspectives. Pictures can often tell more than words, and again www.youtube.com is a rich source (look for 'Niger Delta oil spill'). Dr. Nenibarini Zabbey, Department of Animal Sciences and Fisheries, University of Port Harcourt and Head of the Environment and Conservation Program at the Center for Environment, Human Rights and Development (CEHRD), has provided detailed information about the Niger Delta situation.

Patin (1999), Pokarzhevskii-van Straalen (1996), Andrade *et al.* (2010) and Smith *et al.* (2003) report about treatment of water produced from oil exploration.

Oil sand exploration: Kunzig-Essick (2009) brought the oil sands exploration to the attention of an international audience. The expert panel of the Royal Society of Canada (Gosselin *et al.* 2010) is a comprehensive description of the environmental impact of the oil sand industry. Information from the Oil Sand Developers Group is found at www.oilsandsdevelopers.ca. Other sources are CIA (2011) and BP (2014a).

Coal: National Geographic (April, 2014 issue) presents an interesting reading for the layman about coal. A source of methods for coal mining in the USA is Appenzeller (2006). Youtube is a powerful medium to view coal mining and coal burning (www.youtube.com; search for ‘coal mining’, ‘surface mining’, ‘coal fired power plant’, ‘coal pollution’).

Coal mining is described, for example, in World Coal Institute (2011). The textbook Brown *et al.* (2002) is a good fundamental reading for the treatment of minewater, and Wood (2011) discusses how to avoid minewater disasters.

12

Biofuels

> *The grain turned into ethanol in the US in 2011 could have fed, at average world consumption levels, some 400 million people.*
>
> Lester Brown, director, Earth Policy Institute, Washington D.C. (Brown, 2012).

Climate-change mitigation policies have unleashed the search for more and cleaner and low-carbon energy supplies, for example biofuel energy technologies. Actual statistics on the use of biomass and its composition (firewood, agro fuel and municipal by-products, waste, and so on) are poor and hardly complete. However, there is an apparent relationship between poverty and the use of biomass. The higher the GDP/capita the lower the biomass (total) consumption. A general rule of thumb has been that an additional 10% can be added to global energy consumption for traditional biomass.

It is obvious that biofuel consumes crops that could be used to feed a hungry world. The biofuel consumption creates tension and competition between water used in agriculture for food and fuel production. In fact our need for mobility is weighted against the need for the hungry. The complexity of rising food prices is also coupled to energy. The production of ethanol will add to high and volatile food prices. Ethanol production in both the EU and the US is supported by taxpayer subsidies (see 12.2). The US is the world's biggest producer and exporter of corn and is converting almost 40% of the 2011 harvest into fuel. This has a significant impact on food supplies and prices (Gawain Kripke, Director of Policy and Research, Oxfam America, Washington DC).

Biofuel consumes crops that could be used to feed a hungry world.

One measure of the competition between biofuel and food is that the grain required to fill a 100 liter car fuel tank with ethanol can feed one person for a whole year (Brown, 2012). For people there are no alternatives to food; but for vehicles, there are alternatives to using food-based fuels, for example making the cars more fuel efficient, turning into plug-in hybrids, or – better – to turn into more public transport.

The grain required to fill a 100 liter fuel tank of a car with ethanol just once would feed one person for a year.

12.1 DIFFERENT BIOMASS SOURCES

As discussed in Chapter 9 the poor part of the world population depends on traditional biomass such as firewood, charcoal or crop residues. Biomass is mostly available and affordable, especially for cooking and space heating. Still biomass used in small-scale appliances is rather inefficient and highly polluting.

The so called first generation biofuels include sugar cane ethanol, starch based ethanol, biodiesel (also named methyl esther), and straight vegetable oil. The typical feedstocks used for the manufacturing of the fuels are sugar cane and sugar beet and starch bearing grains (for example corn (maize) and wheat), oil crops (for example canola and palm) and even animal fats. This means that most biofuels today are produced from crops that are also food for humans and animals.

Ethanol can be produced from many different biomass fuels. Bio-ethanol is produced from fermenting any biomass high in carbohydrates. The first generation ethanol is made from starches and sugars.

The second generation technology is developing with raw material from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter. This biomass is not competing as food. Second generation biofuels mainly comprise cellulosic ethanol, which is generally produced through two methods: hydrolysis and fermentation of woody or fibrous biomass, and chemical and thermochemical processes (see Table 12.7 for more details). There are two main differences in the use of biomass and the resulting fuels. One is that the lignin is separated in biochemical conversion. It can be used separately for heat and power production. In the chemical processes the lignin is also converted into syngas. The biochemical processing produces only ethanol. The thermochemical processes, on the other hand, can produce a range of fuels with different properties (Davis *et al.* 2014).

Biodiesels of 2nd or 3rd generation (with waste biomass or with algae) will be very useful in decoupling the energy production from the food demand, and may as well provide interesting complementarities to sanitation schemes.

12.2 THE WATER BIOFUEL NEXUS

It has been recognized for a long time that water is essential to produce bioenergy (Berndes, 2002). To produce the necessary amounts of agro fuel, agriculture requires the input of freshwater for crops. The amount of irrigation water used to grow agro fuel varies significantly from one region to another and depends naturally on climatic conditions, the farming methods, as well as the processing technology used. This is similar to any food production. It is apparent that the irrigation need is quite different in an arid area and in regions with a lot of rain. Actually, about 80% of the crop worldwide is rainfed and provides some 60% of the global crop (IIASA/FAO, 2010). The rest of the cropland, some 20% is irrigated during at least a part of the growing season. The production from the 20% land is about 40% of all the production. Actually most commercial biofuel crops are grown in areas where little irrigation (2–6%) is needed (Williams-Simmons, 2013).

The water need (measured as withdrawal or consumption in m^3/MJ) has to take a number of conditions into consideration, such as:

- *Irrigation volume*: volumes of irrigation water per hectare of cropland;
- *Production*: the mass of biomass produced per hectare;
- *Biofuel volume*: the volume of biofuel produced per mass of biomass;
- *Thermal energy*: the thermal energy that can be delivered by the biofuel.

Globally, the estimated freshwater withdrawals for biofuels crops were around 20 km^3. This is less than 1% of global freshwater withdrawals. Based on this it has been estimated that the water consumption due to irrigation is around 5 liters/MJ (compare Table 12.2), see Williams-Simmons (2013).

Measuring the water withdrawal and consumption for biofuel we distinguish between blue and green water. Blue water is defined as the water in rivers, lakes, wetlands and aquifers that can be withdrawn for irrigation and other human uses. Green water is soil moisture held in the unsaturated zone. This comes from precipitation and is available to plants. Therefore:

- Irrigated agriculture receives blue water from irrigation as well as green water from precipitation;
- Rainfed agriculture receives only green water.

Both blue and green water are commonly considered to be 'consumed' when removed from the usable resource base. Also evapotranspiration (ET) is considered to be a form of water consumption since the water is functionally lost by the system considered.

12.2.1 The big biofuel producers

Brazil and the US are the largest producers of bioethanol, and Germany is the largest producer of biodiesel. At present, biodiesel production worldwide is only one-fourth that of ethanol, almost half of it in Europe (IEA, 2012). Subsidies to biofuels were also the highest in the European Union, at $11 billion, the bulk of them going to biodiesel. In the US $8 billion in 2011 went to biofuels, mainly targeting ethanol (IEA, 2012, Chapter 7). In 2012 the Brazilian government announced a program giving $38 billion in subsidized credit to the ethanol sector (www.biofuelsdigest.com/bdigest/2012/02/27/). Davis *et al.* (2014) provides a detailed background which ecological parameters will determine where to grow bioenergy crops in the world. This includes biophysical and climate factors such as temperature, precipitation, soils and land area.

There has been a remarkable development of ethanol use in the US since 2000. In that year over 90% of the corn crop in the USA went to feed people and livestock, many in undeveloped countries. Less than 5% were used to produce ethanol. In 2013, however, 40% went to produce ethanol, 45% was used to feed livestock, and only 15% was used for food and beverage (AgMRC, 2013). Historically the food and energy economies have been largely separate, but now with the huge increase in biofuel, they are merging. If the food value of grain is less than its fuel value, the market will move the grain into the energy economy. As the price of oil rises, the price of grain follows it upward. This is further discussed in 12.4.

> *Historically the food and energy economies have been largely separate, but now with the huge increase in biofuel, they are merging.*

The US is by far the biggest ethanol producer. The Energy Independence and Security Act, passed by the US Congress at the end of 2007, requires that the nation should produce 15 billion gallons (57 million m^3) of corn ethanol per year by 2015 and reach 36 billion gallons (136 million m^3) by 2022 (Sec. 202, Energy Independence and Security Act of 2007, www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf). While meeting only 10% of Americans' gasoline consumption, that level of production would require massive, permanent increases in the amount of farmland for corn, as well as ramped-up water consumption and pollution. In 2008 one out of 8 liters of gasoline sold in the US contained ethanol. As a result, the cost for farmland, especially in the Midwest was skyrocketing, particularly in Iowa, where more corn is grown and more ethanol is produced than in any other state. The US Government was giving a tax credit to ethanol producers and maintained a tariff on ethanol imported from Brazil.

Brazil is the world's largest sugar producer and exporter. Half of its sugarcane harvest is made into fuel ethanol. With 10% of the world's sugar harvest going into ethanol, the price of sugar is rising.

Here we will mainly discuss the two biofuels that are most commercially interesting, ethanol and biodiesel. In the USA corn is used for biofuel while Brazil uses sugarcane. Table 12.1 indicates how large part of the crop that is irrigated in the respective countries.

Table 12.1 The amount of irrigation for three major biofuel crops.

Produced biofuel crop	Typical area that is irrigated	Maximum observed area that is irrigated
Sugarcane	4% (Brazil)	54% (India)
Maize (corn)	6% (US Midwest)	31% (US Texas)
Soybean	2% (US Midwest, Brazil, Argentina)	6% (US)

Source: Williams-Simmons (2013), Table 3.5.

In Europe, the emphasis is on producing biodiesel. Biodiesel capacity in Europe has increased from a total capacity of 5.8 million m^3 in 2006 to an annual capacity of 24 million m^3 in 2013 (Charles *et al.* 2013). The ethanol capacity in 2013 was around 8.4 million m^3. Most of the biodiesel comes from vegetable oil, mostly in Germany and France while most of the ethanol is distilled from grain in France, Spain, and Germany. EU has a goal to obtain 10% of its automotive fuel from plant-based sources. In order to achieve this EU has been increasingly turning to palm oil imported from Indonesia and Malaysia. This in turn leads to more oil palm plantations while rain forests are sacrificed. It is also important to note that POME (palm oil mill effluent) requires advanced wastewater treatment. As a result the Netherlands and some other EU countries are reconsidering import of palm oil for biodiesel production. In 2006, China converted some 4 million tons of grain – mostly corn – into ethanol. In India, as in Brazil, ethanol is produced largely from sugarcane.

Biomass for biofuel should not be grown in water scarce regions and compete with other uses of the freshwater. Instead, a responsible practice is to grow the biofuels in areas where little irrigation is needed. Then there is an opportunity to choose crops that can withstand drought and survive with little or no irrigation. In particular, lignocellulosic crops should be grown without any irrigation.

12.2.2 Water requirements for biofuel

The water impacts of biofuel production are summarized in Table 9.6, considering both quantity and quality. Water scarcity, rather than land scarcity, may prove to be the key limiting factor for biofuel feedstock production in many contexts.

The largest component of water use associated with bioenergy is the cultivation of feedstocks. Pollution of water by agro-chemicals can also be characterized indirectly as a 'water use' since it may reduce freshwater availability by contaminating water resources. Runoff containing fertilizers, pesticides and sediments (surface and groundwater) will contaminate the water and the refining process will produce wastewater.

Table 12.2 shows the water withdrawal and consumption for various biofuel productions. It is apparent that the consumption varies considerably because of differences in irrigation needs among regions and crops. The minimum numbers in the table indicate the water consumption for non-irrigated crops, where the water requirement takes place in the processing for fuels. For example, rain-fed crops grown in Brazil and Southeast Asia generally make lower demands on water resources than irrigated crops grown in parts of the US. In the IEA data the minimum water *withdrawal* is equal to the minimum water *consumption* for the biofuels. The maximum withdrawal is anywhere between 80% and 450% higher than the consumption. The lignocellulosic crops are intended for rainfed growth so their water consumption is not shown in the table. In the data shown by Williams-Simmons (2013) the withdrawal is shown. The authors claim that the consumption is between 1.5 and 3 times lower.

Table 12.2 Water consumption for energy production of biofuels. The consumptions are given for extraction, processing and transport.

Energy source		Liters/MJ	Energy content[c] MJ/liter	Liters of water per liter of biofuel
Corn ethanol	Consumption	0.14–24[a]	23.4	3.3–560
	Withdrawal	0.14–44[a]		3.3–1000
	Withdrawal	0; 5.2; 26.7[b,1]		0; 120; 620
Sugarcane ethanol	Consumption	0.04–60[a]	23.4	0.9–1400
	Withdrawal	0.04–165[a]		0.9–3900
	Withdrawal	0; 4.4; 60[b,1]		0; 100; 1400
Palm oil biodiesel	Consumption	0.02–0.13[a]	33.0	0.65–4.3
	Withdrawal	0.02–0.7[a]		0.65–23
Rapeseed biodiesel	Consumption	0.02–0.5[a]	33.0	0.65–17
	Withdrawal	0.02–1.25[a]		0.65–41
Soybean biodiesel	Consumption	0.02–15[a]	33.0	0.65–500
	Withdrawal	0.02–27[a]		0.65–890
	Withdrawal	0; 6.9; 21[b,1]		0; 230; 690

[1] The three numbers refer to minimum irrigation (rainfed), majority practice and maximum irrigation level, respectively.

[a] Converted from IEA (2012), Figure 17.3.

[b] Williams-Simmons (2013), Table 3.6

[c] IPIECA (2012)

Data converted from IEA (2012), Table 17.3; US DOE (2006); Gleick (1994); Williams-Simmons (2013), Table 3.6; Compare Table 9.7 for fossil fuels.

FAO (2008) presents some alternative numbers for the water requirement for different crops. Table 12.3 shows not only the final water consumption but also the yield. The oil palm and rape seed plantations are not supposed to be irrigated.

Table 12.3 Water requirements for biofuel crops.

Crop	Annual obtainable crop yield	Energy yield	Evapotranspiration equivalent	Potential crop evapotranspiration	Rainfed crop evapotranspiration	Irrigated crop water requirement	
	liters/ha	GJ/ha	liters/liter fuel	mm/ha	mm/ha	mm/ha[1]	liters/liter fuel
Sugar cane	6000	120	2000	1400	1000	800	1333
Corn	3500	70	1357	550	400	300	857
Oil palm	5500	193	2364	1500	1300	0	0
Rape seed	1200	42	3333	500	400	0	0

[1] On the assumption of 50% irrigation efficiency.
Source: FAO (2008), Table 10.

NRC (2008) describes that the irrigation water applied for corn is about 780 liters of water per liter of ethanol. The 2003 USDA Farm and Ranch Survey states that irrigated corn grain uses on average 0.35 m^3 of water per m^2, which corresponds to an accumulated rain of 350 mm. The average corn yield from this land is 15 m^3/ha (178 bushels per acre). This equates to 785 liters of water for every liter of ethanol produced (compare Table 12.2).

The water footprint (WF) for various kinds of biomass has been estimated by Gerbens-Leenes *et al.* (2009). The authors define the WF as the total annual volume of fresh water used to produce the food. In the paper the WF per unit of energy from biomass has been estimated for 15 different crops, measured in liters/MJ. The assessments have been made for the complete growing season of the plant. It is shown that the WF is quite different in different regions, as summarized in Table 12.4.

Table 12.4 Water footprint of energy from biomass (liters/MJ) for corn and sugar cane in four different countries.

Crop	The Netherlands	United States	Brazil	Zimbabwe
Corn	9	18	39	200
Sugar cane	–	30	25	31

Source: Gerbens-Leenes *et al.* (2009), Table 3b.

For every liter of ethanol from irrigated corn production 600–1000 liters of water are needed.

To generate energy from ethanol produced from irrigated land is questionable from a sustainability point of view. Driving a car using this kind of ethanol would require 600–1000 liters of (irrigated) water per liter of ethanol. This means that while the engine needs some 6 liters of ethanol per 100 km it would consume 3600–6000 liters of water. Consequently, when we consider the fuel mileage of a car we should consider water consumed per km. This water is often extracted from fossil water that will not be replaced for generations.

Besides the disproportional amount of water needed to produce biomass, using biomass to generate energy is not in all cases emitting less greenhouse gases. Therefore, it seems to be highly questionable whether the production and usage of biomass adds value. IPCC (2014a, Chapters 9.3, 13.3 and 22.6) focus the attention on that mitigation efforts focused on land acquisition for biofuel production show negative impacts for the poor in many low and middle-income countries, and particularly for the indigenous people and (women) smallholders.

Energy-related water use rises as a direct consequence of steeply increasing global biofuels supply. IEA predicts in New Policies Scenario (IEA, 2012) that the water use will increase more than four times until 2035, given government policies that mandate the use of biofuels. Water withdrawals for biofuels increase in line with global supply, from 25 bcm to 110 bcm over 2010–2035. However, consumption increases from 12 bcm (2010) to 30 bcm (2020) to around 50 bcm (2035) during that time, equalling the water consumption for power generation by the end of the prediction period. These higher water requirements for biofuels production stem from the irrigation needs for feedstock crops for ethanol and biodiesel – primarily sugarcane, corn and soybean – in major producing regions, such as Brazil, the US and China. Non-irrigated advanced biofuels from waste crops may penetrate the market after 2020. This would dampen the growth in overall water needs for biofuels production.

It should also be noted that various portions of the ethanol production cycle have different kinds of water requirements. For example, in biofuel production irrigation requires orders of magnitude more water than ethanol biorefineries, as shown in Table 12.5. However the intensity of water consumption can be much higher for refineries, where thousands of m^3 of water are to be withdrawn on the spot, significantly changing local hydrology and requiring additional infrastructure to provide that water. The water requirement of fossil fuels were shown in Table 9.7.

Table 12.5 Estimated use of water for various technologies of biofuel production, compared to crude oil (from Voinov-Cardwell, 2009).

	Irrigation use: liters of water per liter of ethanol[1]	Refinery use: liters of water per liter of gasoline or ethanol[1]
Oil	n/a	0.5–1
Corn	0–1900	2–5
Sugar	0–400	6

[1] See Appendix 1 (A1.8) for conversion of units
Compare Tables 12.2 and 9.7.

Pate *et al.* (2007) have estimated the consumptive water use from ethanol productions to 4 liters of water per liter of ethanol produced. As a comparison they estimate the consumptive water use in petroleum refining to about 1.5 liter of water per liter of gasoline. Biodiesel refining requires much less water per unit of energy produced than bioethanol. Pate *et al.* (2007) estimate that about 1 liter of fresh water is required for every liter of biodiesel. The possibility of using recycled wastewater is considered in some refineries.

In a survey of 22 facilities for ethanol production in the USA, representing 37% of the 2006 production the water consumption has been recorded. Table 12.6 summarizes the data (compare Table 9.4). There are significant variations in water use.

Table 12.6 Water and steam use in ethanol production plants (US).

	Dry mills	Wet mills
Water use (liters) per liter of ethanol[1]	2.65–4.9	1.2–6.1
Steam use (kg) per liter of ethanol	0.07–3.5	1.6–5.5

[1] For conversion of units, see Appendix A1.8
Source: Wu et al. (2009).

As indicated the water use in biorefineries is much less than for irrigation. However, the impacts of the water uses are different. The biorefineries generate local, but often intense, water supply demand, while irrigated agriculture can generate regional-scale problems. However if the agriculture is rainfed then water for the biorefinery may be the primary source of groundwater or surface water extraction in the area (see further the discussion in Section 6.2).

12.2.3 Water quality

In the US the National Research Council (NRC, 2008) has proposed a metric to compare the water quality impacts of various crops by measuring inputs of fertilizers and pesticides per unit of the net energy gain captured in a biofuel. Of the bioenergy feedstocks, corn (maize) has the highest application rates per hectare of both fertilizers and pesticides. Per unit of energy obtained, biodiesel requires just 2% of the nitrogen and 8% of the phosphorous needed for corn ethanol. Pesticide use differs similarly. Using this metric, low-input, high-diversity prairie biomass and other native species would also compare favorably to corn.

The Corn Belt of Iowa, Minnesota, Illinois and surrounding states in the US receive enough rain to naturally replenish most groundwater used to irrigate crops. There, the bigger issue is quality, not quantity of water. Maps of nitrate pollution in streams and groundwater fit closely to maps of nitrogen fertilizer use across the nation, especially in the Corn Belt. The National Academy of Sciences found that recent increases in corn production have already led to greater pollution of surface and groundwater. The risk is 'considerable,' says the Academy, that expansion of corn ethanol production will add to the nitrate load of the Mississippi River and expand the oxygen-depleted 'Dead Zone' in the Gulf of Mexico more than 1500 km downstream (NRC, 2008; FAO, 2008).

12.3 BIOFUELS

The two major biofuels, ethanol and biodiesel, will be discussed here. Ethanol is an alcohol and can be produced from corn, sugar cane, sorghum, potatoes, wheat, as well as from cornstalks and vegetable waste. Ethanol used as fuel for cars is mostly sold as a gasoline additive or as E85 (85% ethanol and 15% gasoline), see Appendix 2. The chemical name for biodiesel is methyl esters and is aimed for diesel engines. It is made from natural oils such as animal fats or vegetable oils.

The methods for conversion of the biomass to bioethanol or biodiesel via biochemical, chemical or thermochemical methods are summarized in Table 12.7.

Table 12.7 Principal methods to convert biomass to bioethanol or biodiesel.

	Technology	Description	Current status
Biological routes to bioethanol from carbohydrates	Hydrolysis and fermentation	A bio-chemical process where sugars are fermented into products (particularly ethanol). Where starch-based feedstocks are used, an additional stage – saccharification – is required before fermentation. Then the starches are converted into simpler sugar molecules by enzymatic hydrolysis.	Fully commercial
	Lignocellulosic hydrolysis and fermentation	After various pretreatments to liberate carbohydrates, numerous organism and process variants are being investigated for their ability to convert cellulosic feedstocks into alcohol-based fuels.	Only little commercial-scale activity
Chemical routes to biodiesel from oils	Transesterification	A chemical process where an alcohol (such as methanol) is combined with a vegetable oil to produce a fatty acid alkyl ester.	Fully commercial. Mostly transport fuel.
	Hydrogenation	The chemical process of adding hydrogen to vegetable oils to create hydrocarbon chains.	Commercial. Mostly transport fuel.
Thermochemical routes to fuels or power	Gasification	Thermochemical process using high temperatures (600–1,100°C) to turn biomass into a ‘syngas’ in the absence of oxygen. Syngas is a mixture of carbon monoxide (CO) and hydrogen gas.	Few large-scale commercial successes.
	Pyrolysis	A thermochemical process where the feedstock is subjected to high temperatures (~475–490°C) in the absence of oxygen to produce a liquid ‘bio-oil’, a light syngas or a solid biocharcoal (biochar).	Starting to be commercialized.

From Davis *et al.* (2014), Table 3.5.

12.3.1 Energy balance

One liter of ethanol has about 67% of the energy content of one liter of gasoline. Biodiesel has about 86% energy content compared to diesel. It is worth noting that Henry Ford's first car ran on alcohol, while Rudolf Diesel ran his engine – later called diesel – on peanut oil. Both of them discovered that refined fossil fuel would give more power to the engines.

The energy balance for the production of different biofuels is shown in Figure 12.1. The diagram illustrates how much energy is obtained from the biofuel, given the 'investment' of 1 unit of fossil fuel for the operation. The numbers are further commented below.

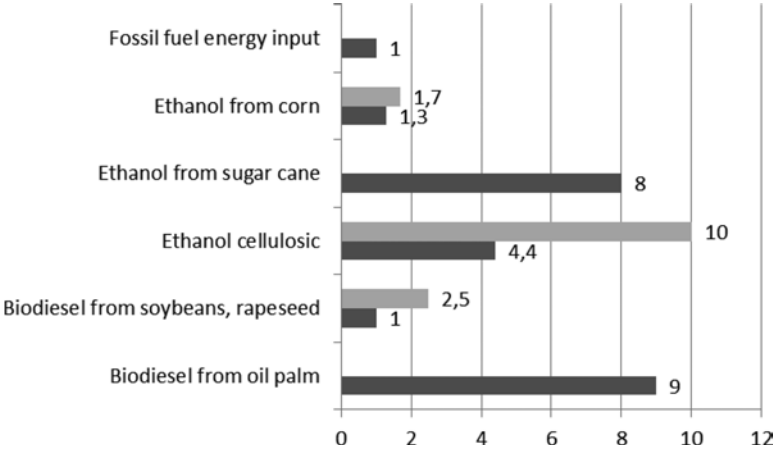


Figure 12.1 The energy balance for different biofuels. The bars show the available energy units from the biofuel after the 'investment' of one unit fossil fuel. When there are two bars, the lower one (black) indicates the minimum estimate and the other bar the maximum estimate. (*Sources:* DOE (2011), Brown (2012), FAO (2008), EPA (2010b)).

The biofuel yields are quite different for different feedstocks and for different countries. FAO (2008) has some estimates of the yield in liters of biofuel per hectare and some key numbers are shown in Table 12.8. The large differences in yield indicate that vastly different land areas for increased biofuel production will be required, depending on the crop and location.

Table 12.8 Biofuel yields (liters/hectare) for different feedstocks and countries.

Biofuel	Feedstock	Global average l/ha	Brazil l/ha	US l/ha	China l/ha	Malaysia l/ha
Ethanol	Sugar cane	4550	5476			
	Corn (maize)	1960		3751	1995	
	Wheat	952				
Biodiesel	Oil palm					4736
	Soybean		491	552		

Source: FAO (2008), Table 2.

12.3.2 Biofuel from corn

Ethanol can be produced from many different plants, but sugar- and starch-bearing crops are much more efficient. Still there are big differences in the yield, as demonstrated in Table 12.8. A major reason is that sugarcane is grown in tropical and subtropical regions all around the year. The growing season for corn is only about 1/3 of a year (FAO, 2008).

Making biofuel from corn requires a lot of energy. Herbicides and nitrogen fertilizers are needed and the soil erosion from corn farming is serious. To make fuel from the corn, the corn is ground, mixed with water and heated. Added enzymes convert the starch into sugars. In a fermentation tank, yeast gradually turns the sugars into alcohol, which is separated from water via distillation. The leftover, called the distiller's grains, is fed to the cattle and some of the wastewater, rich in nitrogen, is applied to the fields as a fertilizer.

The process produces CO_2 since most ethanol plants burn natural gas or coal to create the steam that drives the distillation. On top of that the yeast produces greenhouse gases. Growing the corn requires nitrogen fertilizers, mostly made with natural gas, and use of diesel farm machinery. Some studies of the energy balance of corn ethanol (compare Figure 12.1) suggest that ethanol requires more fossil fuel than it replaces. In other words: if we required that all the energy for today's corn-based ethanol plants – including trucking, lighting, power generation, and distillation – come from the plants' own ethanol production, there would be little ethanol left over. Others give it a slight advantage (as shown in Figure 12.1: 30–70% more energy from the ethanol than was required to produce it). The energy needed to produce corn ethanol has decreased because of improved farming techniques, more efficient use of fertilizers, and higher-yielding crops. How to define the system borders is the topic for many discussions.

The amount of energy output from ethanol is estimated to be between 130% and 170% of the energy needed to produce the ethanol. Other estimates are more pessimistic.

To decrease the carbon footprint the manure from the cows can be used to produce biogas that in turn can replace part of the fossil fuel for the biofuel production, see Chapter 18.

12.3.3 Biofuel from sugar canes

In Brazil ethanol is produced from sugar canes. The Brazilian experience of using ethanol as a petrol additive dates back to the 1920s, but it was only in 1931 that fuel produced from sugar cane officially began to be blended with petrol. Sugar cane is a competitive raw material. The production yield per hectare is about twice as high as that of corn (Table 12.8). A key reason is that the sugarcane grows most of the year in subtropical and tropical areas. Unlike corn, in which the starch in the kernel has to be broken down into sugars using expensive enzymes before it can be fermented, the entire sugarcane stalk is already 20% sugar. It starts to ferment almost as soon as it is cut. Then the waste cane can be burned to power the distillery, lowering the fossil fuel use. This means that sugarcanes require one unit of fossil fuel input to produce 8 energy units from the sugarcane ethanol (Figure 12.1).

Sugar cane for ethanol is grown primarily under rainfed conditions in Brazil. Water availability is not a constraint, but water pollution associated with the application of fertilizers and agrochemicals, soil erosion, sugar-cane washing and other steps in the ethanol production process are major concerns (FAO, 2008). Water withdrawal was around 15–20 m^3/ton of cane in the 1980s in Brazil, when so called open-circuit technology was used for irrigation. Following new legislation related to water resources the water use gradually decreased. Today the water withdrawal is around 1.85 m^3/ton as a result of water recycling and other efficiency measures. Further reuse of water may reduce the water use down to 1 m^3/ton (UNEP, 2011a).

12.3.4 Biofuel from cellulose

Ethanol can also be made from stalks, leaves and cellulose, plant by-products that are normally dumped, burned or plowed back under. Other sources are forestry wastes like wood chips and sawdust and tree bark. Cellulosic ethanol offers more efficient energy conversion, lower greenhouse gas emissions, and reduced water use. Household garbage and paper products can also be used. Breaking up the cellulose molecules and fermenting the sugars could yield large amounts of biofuel. However, one of the great obstacles is the lignin that binds the cellulose molecules together. To unlock the lignin is a key problem also in paper and pulp processes.

Breaking up the lignin is a key technology in making biofuel from cellulose.

There are two main paths to convert biomass to biofuel and biopower: biochemical and thermochemical conversion, see Table 12.7. A lot of research and development is now spent to further develop these methods. More details and further references are found in Davis *et al.* (2014).

12.3.5 Biofuel using bacteria

A company Joule Unlimited (www.jouleunlimited.com) claims that it has developed microbes that harness the sun's energy to convert CO_2 and water directly into ethanol or hydrocarbon fuels. The organisms are photosynthetic and can produce diesel or ethanol with a high yield. When the bioreactors are placed in sunny areas and at full-scale production the company claims that the annual production can be as high as 140 m^3 per hectare of diesel or 230 m^3 of ethanol. The bioreactors do not require arable land. The company has completed its first pilot plant, in Leander, Texas, and testing of diesel and ethanol production processes is under way.

The photosynthetic organisms produce fuel directly that do not need refining. The process is enabled by the discovery of unique genes coding for enzymatic mechanisms that enable the direct synthesis of alkane, olefin, ethanol, and other key molecules. The process allows for brackish water or gray water, nonindustrial waste water from sources such as baths and washing machines to be used.

12.3.6 Biofuels from algae

Biofuels based on algae growth is considered a future generation of energy source. Algae based biofuels have much higher energy yields. Since they are grown in water, they can avoid most of the land use conflicts that characterize corn, sugar and cellulose biofuels, but may of course contribute to water competition and conflicts. Microalgae grow spontaneously wherever there is water and sunlight. The water temperature should typically be 20–24°C. Algae-based biofuels also extend the versatility of end uses beyond previous generations of biofuel since they can be used to create many different types of fuels, including not only substitutes for gasoline or diesel but also photobiological hydrogen gas. The versatility of end uses, fuels and energy carriers (gas, electricity, solid, hydrogen) represents an improvement over the previous generation of biofuels. Algae cost more per unit mass than other second-generation biofuel crops due to high capital and operating costs, but are claimed to yield between 10 and 100 times more fuel per unit area. More details are found in Davis *et al.* (2014).

12.3.7 Alternatives for transportation

The International Institute for Sustainable Development (IISD) has reviewed the costs and benefits for biofuel policies in EU (Charles *et al.* 2013). The authors claim that the CO_2 and climate benefits from replacing petroleum fuels with biofuels like ethanol are basically zero. The report concludes that there are viable alternatives available to EU policy-makers. It would be much more effective, and much less costly, to significantly reduce vehicle emissions through more stringent standards. In terms of emissions savings, the EU's proposed tightening of the current emission standard for passenger vehicles (reducing average fleet emissions from passenger cars from 130 g of CO_2 per km by 2015, to 95 g/km by 2020) provides a viable low-cost policy measure with multiple benefits. The implementation of a 95 gCO_2/km emissions standard by 2020 provides a cost-effective means of abating CO_2 compared to subsidizing the production and consumption of biofuel. With estimated additional manufacturing costs to the automotive industry of € 1,000 per vehicle to move to the stricter emission standards, the cost of abatement is € 133 per tonne of CO_2 avoided, nearly 20 times cheaper than the average CO_2 abatement cost for biofuels.

12.4 FOOD AND BIOFUEL COMPETITION FOR LAND AND WATER

The future increase in the production of liquid biofuels (mostly bioethanol and biodiesel) is expected to have a great impact on land and water use. Global use of bioenergy is expected to grow more than twice the current use by 2035. Heat and power will be the largest consumers. Liquid transport fuels currently account for less than 5% of current bioenergy.

Biofuels use is expected to more than triple in the IEA New Policies Scenario (IEA, 2012), from 1.3 million barrels of oil equivalent per day (mboe/d) in 2010 to 4.5 mboe/d in 2035, driven primarily by blending mandates. Ethanol remains the dominant biofuel and its production will rise from 1 mboe/d in 2010 to 3.4 mboe/d in 2035. Biofuels meet 37% of road transport demand in 2035 in Brazil, 19% in the US and 16% in the EU. The second generation of biofuels is expected to gain market share after 2020 and may make up almost 20% of biofuels supply in 2040. Subsidies to biofuels increase steadily and will make up 20% of cumulative renewable energy subsidies over the period until 2035.

Bioenergy has begun to compete with food production for land and water resources, and this competition is likely to increase as food crops, ethanol and biodiesel feedstock production have virtually the same land suitability requirements. The rises in recent world prices of food have been partly attributed to diversions for liquid biofuels. The massive diversion of grain to fuel cars, in particular in the US, has helped driving up food prices, leaving low-income consumers everywhere to suffer some of the most severe food price inflation in history. As of mid-2012, world wheat, corn, and soybean prices were roughly double their historical levels

(Brown, 2012). Since then the food prices have dropped, in particular during 2014 (IMF, 2014), Table 12.9. Oil prices can play a central role.

Table 12.9 Market prices for some commodities.

		2011	2012	2013	2014 (Oct)
Wheat	USD/MT[1]	316	313	312	245
Corn	USD/MT	292	298	259	163
Soybeans	USD/MT	484	538	517	354
Palm oil	USD/MT	1077	940	764	673
Sugar free market	USD/MT	26	21	18	16.5
Sugar US	Cents/lb	38	29	21	27
Sugar EU	Cents/lb	27	26	26	27
Crude oil spot price (USD/barrel)	USD/barrel	104	105	104	86

[1] MT = US abbreviation for the metric ton
Data from IMF (2014).

The appetite for grain to fuel cars is seemingly insatiable. The grain turned into ethanol in the United States in 2011 could have fed, at average world consumption levels, some 400 million people. If the price of fuel from grain drops below that from oil, then investment in converting grain into fuel will increase. One of the consequences of integrating the world food and fuel economies is that the owners of the world's 1 billion motor vehicles are pitted against the world's poorest people in competition for grain. The winner of this competition will depend heavily on income levels. Whereas the average motorist has an annual income over $30,000, the incomes of the 2 billion poorest people in the world are well under $2,000.

The International Federation of Agricultural Producers (www.ifap.org) has another view. They claim that there are many factors behind the rise in food prices, including supply shortages due to poor weather conditions, and changes in eating habits which are generating strong demand. According to IFAP the proportion of agricultural land given over to producing biofuels in the world is very small: 1% in Brazil, 1% in Europe, 4% in the US, so it is claimed that biofuel production is a marginal factor in the rise in food prices.

The biofuel and food price debate is controversial with a wide range of views. There are a number of impacts and feedback loops involved that can positively or negatively affect the price system. The relative strengths of these impacts are different in the short and long term perspective. The expert debates are also blurred by the use of different economic models and competing forms of statistical analysis, as described in the Biofuel and Food Security Report (HLPE, 2013), a high level expert panel report. The isolated effect of biofuels on food prices, everything else being equal, has been considered in HLPE (2013). When crops are used for biofuels, the first direct impact is the reduction of food and feed availability. This leads to an increase in prices and a reduction of food demand by the poor. Price increases will also spread to other crops, since there is a so called substitution effect both for consumers and producers.

Between 2001 and 2011 the world biofuel production increased five times, from less than 20 billion litres/year in 2001 to over 100 billion litres/year in 2011. The steepest rise in biofuel production occurred in 2007/2008, which coincided with a sharp rise in food commodity prices (HLPE, 2013). Rising food prices can quickly translate into social unrest and in this period there were food riots in the cities of many developing countries. In comparison with average food prices between 2002 and 2004, globally traded prices of cereals, oils and fats were on average 2–2.5 times higher in 2008 and 2011–12, and sugar prices had annual averages of 80%–340% of their 2000–04 prices. These price increases were accompanied by price volatility and price spikes to an extent unprecedented since the 1970s. As an example the tortilla prices in Mexico depend a lot on the price of corn. Corn accounts for around 60% of the final cost of tortillas, which is a staple food for Mexicans. From 2005 to 2011 the prices of tortillas in Mexico rose nearly 70%. This fueled the 2007 riots that led to government price controls. It has been estimated that increased US ethanol production accounted for over 30% of the price spike (National Geographic, Oct 2014).

International food assistance programs have also been hit hard by rising grain prices. Since the budgets of food aid agencies are set well in advance, a price increase will reduce the available food assistance when it is needed. Remember: over 8,500 children are dying each day from hunger and related illnesses (World Food Programme, www.wfp.org/hunger/stats). This is an unnecessary suffering caused by the failure of the current food system. The steeply rising demand for the production of biofuels was identified as an important factor by many observers and a wide range of organizations, from civil society organizations to the World Bank (HLPE, 2013).

There is a mandate from the European Union (EU) requiring that 10% of its transportation energy will come from renewable sources, principally biofuels, by 2020 (ec.europa.eu/energy/renewables/biofuels/biofuels_en.htm, accessed 8 Dec. 2014). Among international agribusiness firms, this is seen as a reason to acquire land, mostly in Africa, on which to produce fuel for export to Europe. Since Europe relies primarily on diesel fuel for its cars, the investors are looking at crops such as the oil palm and jatropha, a relatively low-yielding oil-bearing shrub, as a source of diesel fuel. Many environmental groups, the European Environment Agency, and many other stakeholders object to the deforestation and the displacement of the poor that often results from such 'land grabbing.' They are also concerned that, by and large, biofuels do not deliver the promised climate benefits (see for example EEA: www.eea.europa.eu/themes/energy/bioenergy-and-biofuels-the-big-picture; Greenpeace: www.greenpeace.org/eu-unit/en/campaigns/Climate/Transport-oil-and-biofuels/; Friends of the Earth Europe: www.foeeurope.org/Europeans-forced-drive-rainforest-destroying-biofuels-090913).

It is quite difficult to predict if the very fast increase in biofuels that we now see will continue and how this will influence water and land and other energy resources. Good examples of biofuels will use crops that are grown in rainfed areas, or they may make use of otherwise under-utilized lands. Poor practice, however, can have serious impacts on both the water and land uses. Therefore it is crucial that both good governance and adequate technology are practiced to make the expansion of biofuel production environmentally sustainable. Obviously biomass offers an opportunity for energy production but there are many social, political, economic and environmental conditions that affect the scale of this production. Because none of these conditions are static, there is unlikely to be a definitive calculation for the amount that can be produced.

In the IPCC Special Report on Renewable Energy Sources (SRREN) and Climate Change Mitigation (Edenhofer *et al.* 2011) there is an estimate that 100–300 EJ/yr (or 28,000–83,000 TWh/yr) could be achieved from biomass in 2050. SRREN has reviewed 164 scenarios and the most likely biomass energy is in the range of 80–190 EJ/yr (22,000–53,000 TWh/yr) in 2050. IIASA (the International Institute for Applied Systems Analysis) has published a Global Energy Assessment, GEA (IIASA, 2012) and estimates a potential of 160–270 EJ/year (44,000–75,000 TWh/yr) in 2050. They stress the competing land use demands, problems due to possible deforestation and water availability. The GEA then estimates the potential use to 145–170 EJ/year (40,000–47,000 TWh/yr). A reasonable average of these estimates would be 150–200 EJ/yr (42,000–56,000 TWh/yr) from biomass by 2050. It is certainly a significant increase in current biomass utilization of approximately 50 EJ/yr (14,000 TWh/yr). Implementing all current national liquid biofuel policies and plans worldwide could already take 30 Mha (or 300,000 km^2) of cropland (2% of the current cultivated land), displacing current food crop production and driving further conversion of current forest and grassland (Fischer *et al.* 2010).

Will biofuels slow the climate change? The CO_2 released through their combustion matches the amount of carbon absorbed by the plants from the atmosphere through photosynthesis. From this point of view biofuels appear to be carbon neutral. However, as illustrated in Figure 12.1, greenhouse gases are emitted at all stages from 'cradle to grave' of the biofuels production and uses chain in the production and transportation of feedstocks, during conversion of biofuels, distribution to end user and in final use. Results of various scenario simulations performed by IIASA (2009) show clearly that estimated greenhouse gas savings resulting from expansion of biofuels can only be expected after 30–50 years. Until at least 2030 the net greenhouse gas balances are dominated by carbon debts due to direct and indirect land use changes. For example, the oil palm land expansion in Malaysia and Indonesia and soybean land expansion in Brazil are great threats to the biodiversity.

Liquid biofuel production also places pressure on water resources. Currently, global irrigation water used for liquid biofuel production is estimated to be 1–2% of world total irrigation water use. If all current national liquid biofuel plans were implemented, liquid biofuel production could require 5–10% of worldwide irrigation water (FAO, 2008). Concerns about the competition between biofuels and food may reduce the plans for expansion. Furthermore, there are questions about the extent of net greenhouse gas emissions savings, particularly where forest or grassland has been converted for liquid biofuel production. (Tilman *et al.* 2009). These potential conflicts may force many countries to reassess their production targets. Also, the potential of second generation biofuel has to be further evaluated, since it does not compete with food crops.

12.5 CHAPTER SUMMARY

The water footprint for biomass is generally much higher than for other energy sources and is estimated to be around a factor of 20–100 higher. This means that the 'water mileage' for transportation is very poor. Due to irrigation a car run on corn based ethanol may consume more than 1 m^3 of water for every 10 km. Sugar cane based ethanol is more energy and water efficient than corn based ethanol. There is a lot of development towards the use of cellulose and algae to produce biomass or utilizing photosynthetic organisms to directly produce ethanol or diesel. The energy balances for the different biomass sources of energy are dramatically different.

Bioenergy is now competing with food production for land and water resources, and this competition is likely to increase as food crops, ethanol and biodiesel feedstock production have virtually the same land suitability requirements.

12.6 MORE TO READ

Davis *et al*. (2014) is an excellent introduction into the use of biofuels. The IEA Energy Outlook and the Key World Energy Statistics (IEA, 2014 and earlier reports) contain a huge amount of information (www.iea.org/publications). The Bioenergy Technologies Office of the US Department of Energy has a lot of biofuel information available on their webpage (www.energy.gov/eere/bioenergy/bioenergy-technologies-office). The report by the High Level Panel of Experts on Food Security and Nutrition on Biofuels and food security (HLPE, 2013) is an authorative text on the many controversial issues around biofuel.

13 Cooling thermal electrical power plants

> *Prudence and justice tell me that in electricity and steam there is more love for man than in chastity and abstinence from meat.*
>
> Anton Pavlovich Chekhov

The catastrophic earth quake and tsunami that hit north-eastern Japan on 11 March, 2011 created major damages on the Fukushima Daiichi nuclear reactors. These reactors are boiling water reactors (BWR) of a so called Mark I type and went into service in 1971. The tsunami caused the failure of the in-house backup generator and pumping equipment and this resulted in overheated nuclear cores. This is a dramatic and tragic reminder about the importance of safe and secure cooling of thermal power plants under all imaginable circumstances.

The International Energy Agency estimates global water withdrawals for energy production in 2010 at 1.6 km^3 per day, corresponding to roughly 15% of the global total withdrawals. Around 0.18 km^3 per day (or, 2000 m^3/sec) is consumed. The latter number corresponds to the average discharge of the Nile River at the Aswan Dam.

The water consumption demand from thermoelectric power is growing. In many basins the water demand will compete with rapid growth in the municipal and industrial sectors. Water scarcity will have a significant impact on the electric power generation potential. The amount of water usage is a great concern in many electric power generating systems.

13.1 COOLING THERMAL POWER PLANTS

Thermal power plants, both fossil fuel and nuclear plants, need water for cooling. The cooling water demand was discussed in Chapter 9. Water is an efficient coolant, much more efficient than air, since it has a heat transferring capacity of about four times greater than air.

13.1.1 Water requirement

Thermal power generation uses immense volumes of water and provides roughly 80% of global electric power production. Per unit of energy produced thermal plants are the energy sector's most intensive users of water. Of the total global withdrawals for energy generation roughly 11% are consumed (IEA, 2012). In Europe about 43% of total freshwater withdrawals are for cooling. In some European countries more than 50% of the national water withdrawals are used by thermal power generation (Eurostat, 2010). In the US around 50% of all water withdrawals are aimed at cooling (Wilson *et al.* 2012). In China the withdrawals for power plant cooling is more than 10% of the national withdrawals (Bloomberg, 2013). The water use for power plant cooling is generally much lower in developing countries. In these countries the agriculture is the dominating water user.

The countries or regions with the largest withdrawal and consumption of water for energy production are the world's largest electric power producers, the US, the European Union, China and India. All of them have significant inland generating capacity to meet demand. On the contrary, countries such as Japan, Korea and Australia have minimal freshwater requirements for energy because they can site virtually all of their power plants on the coasts and use seawater for cooling. Water scarcity is a major constraint on water use for energy production in the Middle East. Their power plants are adapted to scarce water conditions and have tried to minimize dependence on freshwater availability.

13.1.2 The cooling process

Thermal power plants heat water that is turned into steam. The steam spins a turbine which drives an electric generator. After passing through the turbine the steam has to be cooled down and condensed to start the cycle again. Apparently all the heat put into the plant that is not converted into electric power is 'wasted' and has to be dissipated into the environment. Most of this heat is removed via the cooling system, usually with water as the medium for heat transfer. A more efficient plant will have less waste heat, thus decreasing the cooling requirement per generated kWh. Typically new natural gas combined cycle (NGCC, see 13.3) power plants (around 50% efficient) require less water than a new coal power plant (38%) and much less than an old coal power plant (efficiencies could be as low as 25%). On the other hand, open-cycle gas turbines, which are usually used as peaking power plants, have no steam cycle and thus do not require water for cooling. In a coal plant with cooling towers, it is estimated that 90% of the water is used in the cooling system. The remaining 10% is used in other processes, such as ash handling and flue gas desulfurization (DOE/NETL, 2010).

There are some options to reuse the waste heat, for example combined heat and power plants. The waste heat is then used for district heating or other types of heating buildings or industrial processes. Treated wastewater can be another cooling water alternative. However, the effluent wastewater quality has to be taken into consideration. The water must be treated in order to avoid corrosion and other undesired effects in the cooling system. In most countries the use of treated wastewater requires that power plant operators obtain additional permits. Actually, in the US wastewater is used for cooling purposes in fifty power plants, for example the nuclear power plant Palo Verde in Arizona, using wastewater as the only source for cooling. Once it has flown through the cooling system, it is pumped to a pond where it evaporates (Union of Concerned Scientists, UCS, 2011).

Also the quality of the cooling water exiting the power plant has to be considered. Once-through cooling discharges (see 13.2) alter the water temperature and cause thermal pollution and changes in oxygen levels in the surrounding environment. Water quality and ecosystems downwind can be affected by air emissions from the thermal power plant, potentially containing mercury, sulfur, and nitrogen oxides, among other chemicals. Fossil fuel power plants also require water for other processes than cooling, such as flue-gas desulfurization, coal washing, and dust removal. This water must be treated to remove toxic chemicals.

13.1.3 Extreme weather

The ongoing climate change will adversely influence thermal power plant production. Extreme temperatures will become more common (see Chapter 4.1), causing hotter air and water temperatures. Cooling processes are constrained by regulations on river flow rates and the maximum allowable temperature for return water. During extremely hot summers in recent years cooling water restrictions have forced several nuclear and fossil-fuel thermal plants to reduce production or completely shut down the operation.

During the heat wave in Europe in 2003 that killed more than 30,000 people, France, Germany and Spain had to choose between allowing reactors to exceed design standards and thermal discharge limits and shutting down reactors. The nuclear power production in France had to be reduced by 7–15%, or the loss of 4–5 reactors (The Guardian, 12 Aug. 2003, www.theguardian.com/world/2003/aug/12/france.nuclear). Electricité de France (EdF) informed that the temperatures of reactor casings in some plants were approaching the 50°C safety limit and attempts to cool them by spraying water from the outside had failed. The rivers Rhone and the Garonne in particular – whose levels were already low – were threatened because nuclear plants were discharging cooling water at more than 30°C, compared with the usual maximum of 24°C. The French nuclear safety authority granted three plants exemptions from cooling water rules: Bugey on the Rhone, Tricastin on the Drome and Golfech on the Garonne. Each one of them were allowed, temporarily, to discharge water at 30°C. In July 2009 another heat wave hit France and the French nuclear reactors produced the lowest level of electricity since 2003, forcing EdF to turn to Britain for additional capacity. EdF have prepared for hot summers on several fronts. The company is stocking more water in reservoirs, offering lower priced contracts to large users in exchange for the right to cut supplies and using more sophisticated forecasting tools for weather and river temperatures (Philippe Huet, executive vice president at EdF).

Several lessons can be learnt from the tragedies due to the heat wave. Considering the risks for many future extreme weather events like the 2003 heat wave it is crucial to learn as much as possible from the tragedies. The first descriptive studies of the 2003 heat wave by the French Institute of Public Health Surveillance (InVS) (Vandentorren *et al.* 2006) found that most of the heat-related deaths occurred among the community-dwelling elderly, that is, those living in their own home – alone or with others. Identifying the risk factors for these deaths is an important public health priority to prevent a repetition of this toll in future heat waves. A case–control study was conducted to determine individual risk factors for death in this population and thereby help define effective public health strategies for population groups at high risk.

In the hot summer of 2012 in the US the 880 MW Millstone nuclear plant in Waterford, Conn., had to shut down because of something that its 1960s designers never anticipated: the water in Long Island Sound was too warm to cool it, 24.8°C (76.7°F) exceeding the limit of 23.8°C (75°F). It was the first time in the plant's 37-year history that the water pulled from the Long Island Sound was too warm to use. A number of similar heat and drought related collisions between water and energy in US nuclear and coal-fired plants have been reported for the period 2006–2012 (Union of Concerned Scientists, UCS, 2012): (1) incoming water too warm, 8 cases, (2) outgoing water too warm, 12 cases, and (3) not enough water, 7 cases.

Also river flows can drop near or below intake structures at the power plants, halting the operations. Higher temperatures also will decrease the effectiveness of water as a medium for cooling, thus potentially lowering the thermal efficiency. This will lower the electricity output or force the plants to shut down.

Climate change will make the heat wave problems more frequent. There is no doubt that electric power generation has to depend more on renewable sources, less depending on water availability.

13.2 DIFFERENT COOLING SYSTEMS

All thermal cycle plants require large amounts of water for steam, cooling and condensing. The amount of water needed is reduced as boiler temperatures are increased. Coal burns at very high temperatures. Therefore coal plants require less cooling water than nuclear plants that operate at somewhat lower temperatures. In nuclear reactors the water demands in a pressurized water reactor (PWR) and in a boiling water reactor (BWR) are about the same.

> Coal plants require less cooling water than nuclear plants

Two broad categories of cooling system are available: once-through and re-circulating, which is further divided into wet, dry and hybrid systems. Each involves trade-offs in terms of water use, impacts on water quality, plant efficiency and cost. The three most common coolings methods are:

- *open loop or once-through cooling systems* – withdraws water, fresh or saline, for one-time use and returns nearly all the water to the source;
- *closed loop systems* – water is recirculated through the use of cooling towers;
- *dry cooling systems* – cools by use of fans.

Hybrid wet-dry systems exist, but are not widely used. They are essentially dry systems with just enough wet cooling to maintain needed generation efficiency during the hottest days of the year. Table 13.1 gives an summary of the advantages and disadvantages of the different systems.

13.2.1 Open loop systems

In the once-through cooling system, water from the nearby lake, river or ocean flows through the condenser tubes. Steam flowing through the condenser outside the tubes gets cooled down and converted back into water. The condensed water is re-used by the plant to make more steam. The water exiting the condenser tubes is warmed up as high as 15°C and returns to the water body. A once-through cooling system is the cheapest option for cooling.

Water for cooling does not have to be fresh water. A power generation site located at the coast can use seawater and does not need cooling towers. There is the added benefit that discharge temperatures would have less effect on the environment.

EXAMPLE: REQUIRED COOLING FLOW IN NUCLEAR REACTORS WITH ONCE-THROUGH COOLING.

The required cooling water flow rate Q_{cool} (m^3/s) in an open loop nuclear plant can be roughly estimated from:

$$Q_{cool} = 0.5\frac{MW_e}{\Delta T}$$

where MW_e denotes the electric power output (in MW) from the nuclear reactor and ΔT (in °C) the differential temperature of the cooling water passing through the condenser. This means that for a typical 1000 MW_e nuclear reactor the required cooling water for a 15°C cooling water increase will require about 33 m^3/s of cooling water. If only a 10°C cooling water increase is accepted then the cooling water requirement will increase to 50 m^3/s. Some rules of thumb say that the cooling water requirements are around 1.5–2.6 m^3/minute per MW. Then a 1000 MW plant will require some 25–43 m^3/s of cooling water.

Table 13.1 Comparison of different cooling systems.

Cooling system	Advantages	Disadvantages
Once-through [open-loop]	Low water consumption; Mature technology; Lower capital cost; Highest performance/plant efficiency.	High water withdrawals; Impact on ecosystem; Exposure to thermal discharge limits.
Wet tower [closed-loop]	Significantly lower water withdrawal than once-through; Mature technology; High performance.	Higher water consumption than once-through; Lower power plant efficiency (slightly lower performance than once-through); Higher capital cost than once-through; (Thermal plumes).
Dry	Zero or minimal water withdrawal and consumption.	Higher capital cost relative to once-through and wet tower; Lower plant efficiency, particularly when ambient temperatures are high (hot, dry days); Larger land area requirements.
Hybrid [wet-dry]	Lower capital cost than dry cooling; Reduced water consumption compared with wet tower; No efficiency penalty on hot [wet] days; Operational flexibility.	Higher capital cost than wet tower; Limited technology experience.

Source: Adapted from Table 17.2 in IEA (2012).

Even if the abstraction is very high the water loss in open loop cooling is relatively small, some 3% of the water withdrawn. However, with increasing water scarcity open loop cooling becomes a less viable cooling alternative. Water quantity problems related to water withdrawal are described in Example 7 in Chapter 2.1. Also the water quality may be affected, for example the dissolved oxygen levels, and some chemicals may be contaminating the water. Water being discharged from nuclear plants can contain radioactivity. The most apparent consequence is of course the temperature. If the cooling water is a major fraction of the river water flow then the thermal consequences become serious. Too high water temperatures can be detrimental to aquatic life and ecosystems. Therefore there is mostly an upper limit of the effluent cooling water, typically 25–30°C. Consequently, if the intake temperature becomes too high (25°C has been increasingly common in hot summers) then there is no longer any capacity left for cooling. Another temperature limit is the water temperature inside the reactor, and a typical maximum is 50°C. The permitting requirements have been increasingly stringent for once-through systems, for example in the US, where existing open loop systems are gradually being phased out. IEA predicts (IEA, 2010) that by 2035, withdrawals could increase by 20% and consumption by 85%. This development is driven via a shift towards higher efficiency power plants with more advanced cooling systems (that reduce water withdrawals but increase consumption), but also an increased production of biofuel (see Chapter 12).

Open loop wet cooling systems are still dominating in many countries. For example, these old type of thermal power plants are a great concern in India, where water scarcity and water quality are critical problems. The geographical distribution of existing thermal power plants shows that more than 80% of them are located in water scarce or water stressed regions. India's Ministry of Environment and Forests banned the construction of open loop cooling systems already in 1999. The only exception is for plants located at the coast, where seawater can be used. Still some 25% of the plants in India use open loop cooling (UN WWDR, 2014, Chapter 21). In the US some 43% of the plants use once-through cooling systems. More of these systems were built before 1969. Most of the cooling systems installed later use closed cycle systems cooling.

13.2.2 Closed cycle systems

In a closed-cycle cooling system the cooling water leaving the condenser flows to a cooling tower, spray pond, or cooling pond. Such a system is called wet recirculating or wet closed loop systems. Inside a cooling tower air is moved upward past water spraying downward. This will cool the water. The water collected in the cooling basin is pumped back to the condenser for re-use. Water from the nearby water body is needed to compensate for the evaporated water from the cooling tower. The columns of steam above many thermal power plants cause many people to assume that massive quantities of water are consumed. In recent years, also recycled wastewater (greywater) has been used in cooling towers. The closed loop (recirculating) system obviously withdraws much less water than the open loop system, only 1–2% of the open loop system, thus reducing exposure to risks posed by constrained water resources. However, the closed loop system consumes more water through evaporation. Also, the land area requirements are greater for closed loop cooling. According to World Energy Council (WEC, 2010a) wet recirculating cooling systems are approximately 40% more expensive than once-through cooling systems.

Closed loop cooling withdraws much less water than open loop cooling but consumes more water through evaporation.

The cooling water systems operation can mostly be made more efficient by good control. To improve efficiency means to reduce the water consumption. The cooling tower is a single component in a larger cooling water system. This means that operating efficiency, water consumption and energy use have to be assessed not only for the cooling tower itself but for the whole system. Generally, the cooling tower is designed for the maximum outdoor air wet bulb temperature of the year. The rest of the time the tower has the potential to either produce cooler water or to be controlled to minimise water and energy use. Mostly cooling towers are controlled with respect to the temperature of the water leaving the tower. The criterion then can be (1) the coldest possible temperature, (2) the highest allowable temperature or (3) a specific leaving water temperature. The temperature can be controlled either by air flow control or by water flow control.

The fans and the pumps are the dominating energy users in a cooling tower. Variable speed fans for the air flow or the water flow offer good potential for control (see Chapter 16) and can significantly reduce tower energy consumption. Variable speed drives offer additional benefits, like noise reduction, smoother operation and a longer operating life.

13.2.3 Dry cooling

In a water scarcity area it may be prohibitive to use water for cooling. Then a dry cooling tower or radiator can be used and the system is cooled directly with air over a radiator (similar to those in automobiles). Such a plant system will have a lower efficiency and a higher energy demand that a wet cooling system. The cooling temperature depends on the relative humidity of the air, but typically dry cooling can only cool down to the ambient air temperature. Ironically the dry cooling systems are best in wet and cold climates but are mostly needed in dry and hot regions, for example in China, Morocco, South Africa and south-western USA. Therefore dry cooling systems leave the temperature higher than water based systems. The plant efficiency will consequently be smaller for a dry system. A typical loss of efficiency is around 2% but under extreme and hot weather conditions the efficiency loss may be as high as 25%. Also, the overall construction cost of a dry system thermal power plant is higher. Estimates by the World Energy Council (WEC, 2010a) say that dry cooling systems are 3–4 times more expensive than wet recirculating systems. Naturally, the impact on the overall cost of the plant depends on its size and type. It has been estimated that cost reductions of 25% to 50% are needed for air cooled condensers (ACC) to become economically competitive in most regions of the world (Ku & Shapiro, 2012).

Table 13.1 gives a qualitative comparison of the three cooling principles.

Table 13.2 summarizes the global average of the various cooling types for the two most common thermal power plant types.

Table 13.2 Cooling types (in %) for coal-fired and nuclear power plants, a global average.

Cooling type	Coal	Nuclear
Once-through fresh	25	23
Once-through saline	21	44
Wet-tower	50	33
Dry	4	0

Source: Platts (2011).

13.3 DIFFERENT TYPES OF THERMAL POWER PLANTS

Many different thermal power plant technologies have been developed or are under development. These systems have a potential to reduce the water consumption. Coal is still the single largest source of electrical power.

13.3.1 Pulverized Coal (PC) plants

This plant has a coal-fired boiler that generates the thermal energy by burning pulverized coal (also called powdered coal or coal dust) that is blown into the firebox. By using the coal in powder form the whole volume of the furnace is used for the combustion. The fine grain coal is mixed with air and burned. The powdered coal from the pulverizer is directly blown to a burner in the boiler. The burner mixes the powdered coal in the air suspension with additional pre-heated combustion air and forces it out of a nozzle similar in action to fuel being atomized by a fuel injector in modern cars. Under operating conditions, there is enough heat in the combustion zone to ignite all the incoming fuel. This type of plant dominates the electric power industry. As noted in Chapter 11.8 the coal consumption in this type of plant is around 8 tons of coal every minute for a 1000 MWe power plant.

There are three major categories of pulverized coal power plants, subcritical, supercritical and ultra-supercritical. The main difference between the three types of pulverized coal boilers are the operating temperatures and pressures. Subcritical plants operate below the critical point of water (374°C and 22 MPa, around 220 bar). Supercritical and ultra-supercritical plants operate above the critical point. As the pressures and temperatures increase, so does the operating efficiency. The efficiency ranges for the three types are:

- *Subcritical*: around 37%;
- *Supercritical*: around 40%;
- *Ultra-supercritical*: 42–45%.

A majority (90%) of all coal-fired plants in the world are traditional subcritical PC plants. As an example among new plants, the coal-fired plant Medupi in South Africa with a final capacity of 6 * 800 MW is a supercritical coal fired power plant. It is expected to have an efficiency that is around 20–25% higher than the existing plants – reducing CO_2 by about 10% per kWh produced and also resulting in lower water use per unit of power generated (Alstom, 2009).

13.3.2 Gas turbines

In a gas turbine air is used instead of steam to rotate the turbine. Air with atmospheric pressure is flowing through a compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This gas having a high temperate and high pressure enters a turbine, where it expands down to the exhaust pressure. This process will produce mechanical power in the turbine. The turbine shaft work is used to drive the compressor and other devices such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work comes out in the exhaust gases, so these have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. Gas turbines are used to power both aircraft jet engines and electrical generators.

13.3.3 Integrated Gasification Combined Cycle (IGCC)

In an IGCC plant a gasifier will turn coal and other carbon based fuels together with water and air (or oxygen) into gas, a synthesis gas, or syngas. Syngas is a mixture primarily of methane (CH_4), carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and water vapor. The process can be summarized in the simplified reaction:

$$3C \text{ (i.e., coal)} + O_2 + H_2O \rightarrow H_2 + 3CO$$

More hydrogen can be produced by additional reaction with water vapor:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The impurities are removed from the syngas before it is combusted. Some pollutants, such as sulfur, can be made re-usable. Air emissions of sulfur dioxide (SO_2), particular matter and mercury are usually removed.

Excess heat from the primary combustion and syngas fired generation is then passed to a steam cycle. This gives an improved efficiency compared to conventional pulverized coal. The plant is called *integrated* because (1) the syngas produced in the gasification section is used as fuel for the gas turbine in the combined cycle, and (2) steam produced by the syngas coolers in the gasification section is used by the steam turbine in the combined cycle. An IGCC plant improves the overall process efficiency by adding the higher-temperature steam produced by the gasification process to the steam turbine cycle. This steam is then used in steam turbines to produce additional electrical power.

A major problem for the IGCC technology is its high capital cost. There are quite varying estimates of the real cost per installed MW. If carbon capture storage is installed, then the IGCC may be more attractive than a pulverized coal plant, but the costs may be prohibitive, as discussed in Section 13.4. Even if the IGCC seems to be a promising technology to utilize coal there is still a controversy, if capital costs should be spent on coal fired power plants, considering the global warming. The alternative would be to use the funds for the development of new renewables.

13.3.4 Combined Cycle Gas Turbine (CCGT)

In a CCGT plant a gas turbine generates electricity and the waste heat is used to make steam, generating additional electricity via a steam turbine; this last step enhances the efficiency of electricity generation. CCGT plants are usually powered by natural gas, although fuel oil, synthetic gas, or even biofuels can be used. The major part of water consumed in a CCGT plant is used for cooling. It is estimated that the water consumption is about the same as in IGCC plants.

13.3.5 Natural Gas Combined Cycle (NGCC)

An NGCC plant works similarly to a CCGT plant. The majority of water used in a NGCC plant is for cooling. In North America and Europe, most new gas power plants are of this type. The water consumption is low compared to all other fossil fuel fired power plants.

13.3.6 Nuclear power

A nuclear reactor produces and controls the release of energy from splitting the atoms of uranium, mainly the isotope uranium 235. The energy released is used as heat to make steam to generate electricity. Most types of reactors use the same principles for using the nuclear power to produce electricity. The energy released as a gas or water, and is used to produce steam. The steam is used to drive the turbines which produce electricity, as most fossil fuel plants.

A pressurized water reactor (PWR) has water at over 300°C under pressure in its primary cooling/heat transfer circuit. The steam generated is transferred in a steam generator into a secondary circuit. The steam is this circuit drives the turbine. A boiling water reactor (BWR) makes steam in the primary circuit above the reactor core, at similar temperatures and pressure. Both types use water as both coolant and moderator, to slow neutrons. The steam temperatures and pressures in nuclear reactors are lower than in a coal-fired plant. This is for safety reasons. As a consequence nuclear reactors are less thermally efficient and will require more water per power unit for cooling. A coal and gas fired plant will lose some heat via the emission of flue gas to the atmosphere. Since a nuclear reactor has no corresponding emission to the atmosphere it simply has to get more cooling via the cooling system. It was demonstrated with frightening clarity in Fukushima that water in large quantities also has to be available for cooling of spent uranium fuel rods. The spent fuel, stored in a separate pond, still produces heat. Therefore plenty of circulating water has to be available for cooling the pond water.

At the end of 2013 there were 434 nuclear reactors in operation in the world. Most of them are PWR (273) and BWR (81). Together all the reactors have a capacity of 372 GWe (International Atomic Energy Agency data 2013).

We have noted that the cooling water capacity depends on the temperature. As a result the electrical power output can vary slightly from summer to winter. With the winter water temperature cooler the plant can produce more energy. For example, the Watts Bar PWR in Tennessee, US is reported to run at about 1125 MWe in summer and about 1165 MWe in winter, due to the different condenser cooling water temperatures.

13.3.7 Geothermal power

The concept behind geothermal power generation is simple. Drill a hole deep into the earth to tap into a pressurized area of hot water and steam. Pipe the steam to the surface and use it to drive a turbine to generate electricity.

The steam cycle used in geothermal power resembles the steam loop in a coal power plant or a nuclear power plant. Some regions are more suitable for geothermal power generation than others. It depends on how far from the surface hot areas are located. The Pacific 'Rim of Fire', known for the high incidence of volcanoes is especially suited for geothermal energy production, but many other parts of the world are as well. Heat from hot springs has been used directly since ancient times.

Today the total installed capacity of geothermal power is about 11,000 MW. In 2010 the world production was 68 TWh (IEA, 2012, Table 7.2). For a comparison, the world hydropower generation was 3431 TWh and windpower production 342 TWh in 2010.

13.3.8 Concentrated Solar Power (CSP)

The basic principle of Concentrating Solar Power is simple. Sun light is focused into a small area by using mirrors and/or lenses. The concentrated sun light can be used in two ways:

- *Generate heat*: this is the principle commonly used in many large CSP systems, and they are consequently called Concentrating Solar Thermal. The heat generated by the concentrated sunlight, with temperatures up to 1000°C, is used to heat fluids that are the source for power generation. The fluid can be fresh or salt water. When the solar energy is concentrated on a furnace the water inside it can be heated to steam.
- *Making photo-voltaic (PV) panels more efficient (see Chapter 22.2)*: By concentrating the sunlight the amount of light rays (photons) received by the surfaces on the PV panels is simply increased.

Most concentrating solar thermal systems are found in the US and in Spain. Together their capacity is around 2000 MW (IRENA, 2012a). In 2010 the total electric power production was 2 TWh (IEA, 2012, Table 7.2). The water cycle reminds about the one in nuclear reactors. Wet cooling is the most common technology.

There are two major CSP types: trough systems and tower systems. In a trough system curved mirrors are used to focus the solar energy onto a receiver tube that runs down the center of a trough. In the receiver tube, a high-temperature heat transfer fluid (such as synthetic oil) absorbs the heat and can reach a temperature of about 400°C. It is led through a heat exchanger to heat water and produce steam. The steam drives a conventional steam turbine power system to generate electricity. A typical solar collector field contains hundreds of parallel rows of troughs connected as a series of loops.

A tower system represents a central receiver system. Here flat mirrors (called *heliostats*) track the sun along two axes and focus solar energy on a receiver at the top of a high tower. The focused heat energy will heat a transfer fluid (typically 400°C – 550°C) to produce steam and run a central power generator. The higher temperature will favor a higher efficiency.

Water is used not only in the turbines but also for cleaning the mirrors, but the latter use is only a small fraction of the water used for cooling. Since most CSP plants are located in arid areas water scarcity becomes a problem and motivates the used of brackish or salt water.

13.3.9 Water requirements

The water requirements for different types of thermal plants and cooling systems are shown in Table 13.3. Note that there are large uncertainties in the data. There are different estimates of the water needs comparing Table 13.3 and Table 9.6. Carbon capture is discussed in the next section. The general tendency of the water consumption – both for once-through cooling and for wet-tower cooling – is that the consumption will decrease as the efficiency of the plant will increase. Also, once-through cooling will consume less than wet-tower cooling. The highest water consumption is for PC plants with carbon storage and then follows with decreasing consumption, nuclear power, solar thermal, IGCC and finally NGCC plants.

Once-through cooling consumes less water than wet-tower cooling.

Figures 13.1 and 13.2 summarize the key numbers of Table 13.3 and shows the maximum and minimum values estimated in different sources. It also demonstrates the degree of uncertainty in the data available. In particular the water needs for geothermal and concentrating solar power (CSP) technologies have a wide range. This depends on the specific generating technology and the cooling system. The geothermal water consumption is not shown in Figure 13.2.

A supercritical coal fired power plant with once-through cooling will withdraw roughly 15% less water than a subcritical plant. Also water consumption will decrease by around 15%. Also for a supercritical coal-fired power plant with a wet cooling tower the water consumption is some 15% less than for a subcritical plant (Wilson *et al.* 2012).

Wilson *et al.* (2012) have also calculated the water footprint for the average US consumer of electric power. The various electric power sources have been weighted together (2009 data) where coal contributes with 44.5%, hydroelectric 6.8%, natural gas 23.3%, nuclear 20.2% and other sources 5.2%. Then the consumption of freshwater is estimated to 4.1 m^3/MWh. Evaporation from hydro dams (2.3 m^3/MWh) will contribute to make the number higher than the data found in Table 13.3 (see further Chapter 10).

Table 13.3 Water use and consumption for thermoelectric power generation.

Plant type	Cooling process (open/closed/dry)	Water use m^3/MWh (el)*		
		Steam condensing		Other uses
		Withdrawal	Consumption	Consumption
PC steam turbine	Open	75–190[a,d]; 142[b]; 72–520[e]	0.8–1.2[a]; 0.38[b]; 0.4–1.2[d]; 0.24–1.5[e]	0.12[a]
	Closed	1.2–2.4[a]; 4.5[b]; 1.9–4.5[d]; 1.7–7.2[e]	1.2–2.0[a]; 4.2[b] 1.8–4.2[d]; 1.4–5.8[e]	
	Dry			0.66[c]
PC steam with CCS	Closed	4.1–9.3[e]	3.0–6.7[e]	
Nuclear steam turbine	Open	95–225[a,d]; 174[b]; 90–315[e]	1.6[a]; 0.38[b]; 0.4–1.9[e]	0.12[a]
	Closed	2–4.4[a]; 5.7[b]; 2.9–12.4[e]	1.6–2.9[a]; 5.7[b]; 2.1–5.2[e]	
Gas combined cycle	Open	30–80[a,d];	0.4[a]; 0.08–0.38[d]	0.04[a]
	Closed	0.9[a]; 0.56–1.07[d]	0.7[a]; 0.5–1.1[d]	
	Dry			0–0.015[d]
Coal IGCC	Closed	0.8[a]; 1.1–1.2[b]; 1.3–3.7[e]	0.7[a]; 1.2–2.8[e]	0.6[a]
Coal IGCC with CCS	Closed	1.7–4.2[e]	1.9–3.9[e]	
Gas CCGT	Open	26–100[e]	0.01–0.4[e]	
	Closed	0.6–1.1[e]	0.6–1.1[e]	
	Dry			0.007–0.023[e]
Gas CCGT with CCS	Closed	1.8–3.9[e]	1.4–2.8[e]	
Geothermal steam	Closed	8[a]; 0–19[e]	2–5.5[a]; 0–19[e]	0.2[a]
CSP (tower)	Closed	~ 2.8[a]; 0–3.9[e]	~2.8[a]; 0–3.9[e]	
CSP (trough)	Closed	2.9–3.5[a]; 2.7–4.2[d]; 0–3.9[e]	2.9–3.5[a]; 2.7–4.2[d]; 0–3.9[e]	0.04[a]
	Dry			0.296[c]; 0.16–0.3[d]
Solar PV	N/A	0	0	0.01[a]; 0.13[e]
Wind	N/A	0	0	0.01[a]; 0.0038[c]; 0.002[e]

Notes: CCS = carbon capture and storage; IGCC = integrated gasification combined-cycle; CCGT = combined-cycle gas turbine; CSP = concentrating solar power; Solar PV = solar photovoltaic; Water used for the production of input fuels is excluded.
Fossil steam includes coal-, gas- and oil-fired power plants operating on a steam cycle.
*See Appendix 1 (A1.8) for conversion of units.
Sources: (a) DOE (2006), Table B-1, (b) World Energy Council (WEC, 2010a), Table 6. Compare Figure 9.10, (c) Inglesi-Lotz and Blignaut (2012), (d) Macknick *et al.* (2012), (e) converted from IEA (2012), Figure 17.4.

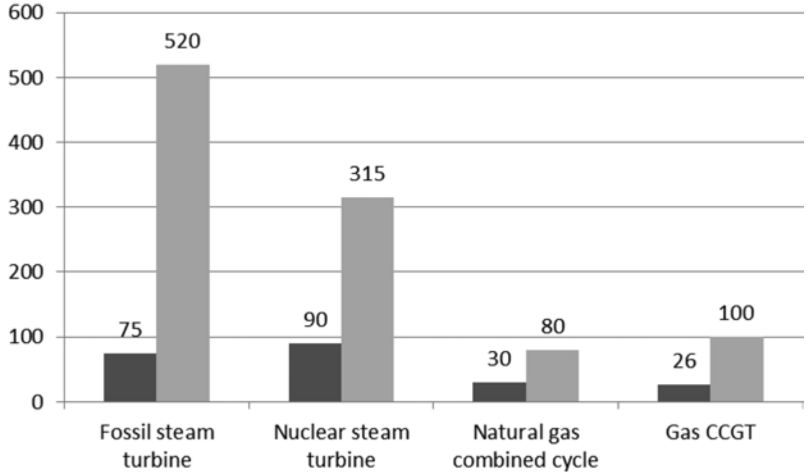


Figure 13.1 Summary of the water withdrawal (m³/MWh) for once-through cooling in thermoelectric power generation. The left bar for each plant type indicates the smallest water withdrawal found in the literature. The right bar shows the maximum value. (*Sources*: see Table 13.3).

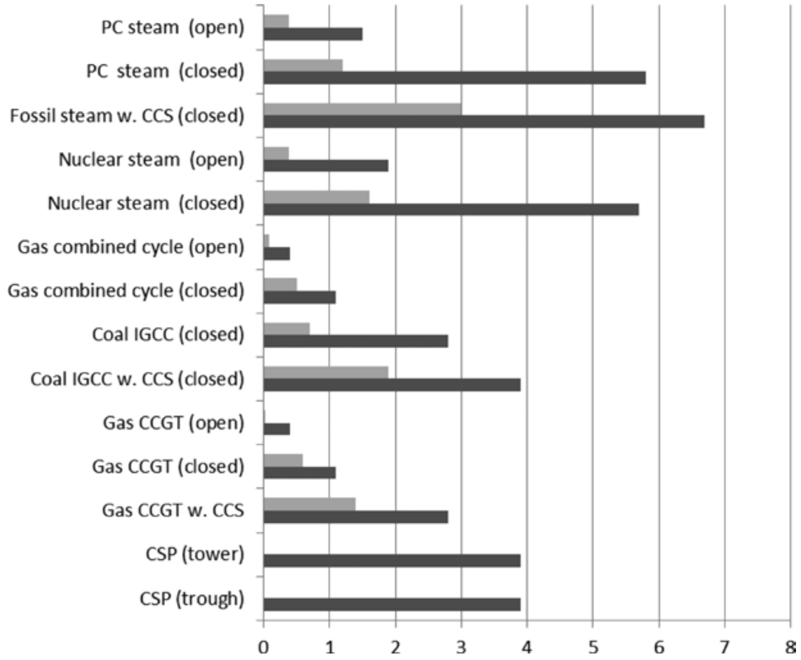


Figure 13.2 Summary of the water consumption (m³/MWh) for once-through (open) and wet-tower (closed) cooling in thermoelectric power generation. The upper bar (grey) for each plant type indicates the smallest water consumption found in the literature. The lower bar (black) shows the maximum value. (*Sources*: see Table 13.3).

13.4 CARBON CAPTURE AND STORAGE (CCS)

Carbon capture and storage aims at capturing CO_2 from large point sources, like a fossil fuel power plant, before the gas is emitted to the atmosphere. The gas has to be transported to an injection site and be injected into deep geological formations for storage. There has been a lot of interest in CCS to reduce greenhouse gas emissions as fossil fuels will be used for a long time for electrical power production (IPCC, 2005; IEA, 2008, Chapter 6). However, carbon capture takes energy and that will translate to additional water use. Or, to cite Jared Ciferno, technology manager for the existing plants program of the National Energy Technology Laboratory (NETL): 'This technology was not developed in a water-constrained environment' (DOE/NETL, 2010).

Although carbon capture technology is commercially available today there are currently very few large-scale commercial CCS power plants projects in operation. Part of the explanation is the high capital costs of the technology and the sustained operating costs. Another hurdle to reduce carbon emissions is the high additional water consumption (DOE/NETL, 2010; Hussey *et al.* 2013). Additional electric power is needed to run auxiliary equipment such as pumps, fans, and compressors for the CO_2 capture stream. This means that more fuel inputs are required to achieve the same electricity output, resulting in additional amounts of cooling water per kWh generated. Future energy trends will naturally depend on the rate at which the efficiency of current energy technologies will improve and new be developed. Also IEA points out that there are great uncertainties around the prospects for carbon capture (IEA, 2012, Chapters 1, 5, 8, 11).

The US Department of Energy is supporting an ambitious Carbon Capture R&D Program at the National Energy Technology Laboratory (Ciferno, 2011; Taylor, 2011). So far several barriers to incorporate CCS technology in coal-fired power plants have been identified:

- The electrical energy output will decrease some 20–30% due to decreasing efficiency, see Table 13.4.
- Current cost for electricity (for a typical 550 MWe plant) will increase by around 80%
- The added capital cost for CCS in such a plant will be 1500–2000 US$/kW.
- The water consumption will increase significantly, as shown in Figure 13.2 and Table 13.4.

Table 13.4 Plant efficiency decrease and water use increase with carbon capture and storage in thermoelectric power plants.

Technology	Plant efficiency %		Water withdrawal	Water consumption
	without CCS	with CCS	increase %	increase %
Subcritical steam turbine	36.8	26.2	95	80–120
Supercritical steam turbine	39.3	28.4	90	100–117
IGCC coal			60	38–73
NGCC	50.2	42.8	110	

Sources: DOE (2006), DOE/NETL (2010), Taylor (2011).

Carbon capture technology added to thermal power plants will significantly reduce the power efficiency and increase the water consumption.

Table 13.4 summarizes some findings of the reduction of efficiency and the increased water withdrawal and consumption when CCS is added. In other words, the water needs can more than double water requirements for CCS power plants compared to the non-CCS ones with the same cooling system. This can be an issue for local water resources, especially in areas where the impacts of climate change can increase water scarcity or increase water temperature.

The World Bank (2013) report estimates the efficiency of a new (supercritical) coal power plant to 38%, and the addition of CCS will reduce the efficiency down to 33%, a decrease of 15%. Referring to the Table 13.4, let us assume a 25% efficiency reduction using CCS. This implies that around 25% more fuel has to be used to produce the same amount of electrical power output. It also will require 25% more water for cooling per generated MWh. For example, a 500 MWe supercritical plant with 39.3% efficiency will need 1270 MW thermal power. If CCS is added, then almost 140 MWe will no more be available for the customers.

As Table 13.4 demonstrates the water withdrawal and consumption will typically be doubled when CCS is added. This in turn may lead to increasing competition for water with other sectors. Thus, in order to ensure sustainable growth, the water aspects of CCS cannot be overlooked and must be incorporated into decision-making processes.

The high water requirements associated with thermal power plants mean that water availability must be strongly considered in plant siting. This applies, in particular, to nuclear plants and to fossil fuel-based plants fitted with CCS equipment.

13.5 CHAPTER SUMMARY

The global water consumption demand from thermoelectric power is growing. There will be an increasing competition between different uses and users of water. This will have an impact on the electric power generation potential. Open (once-through) cooling systems require much more water than closed cycle cooling systems. However, the latter ones consume more water through evaporation. Still, many once-through cooling systems may have to be replaced by wet-tower closed loop cooling in order to reduce the water withdrawal in water scarce areas. In a dry system a dry cooling tower or radiator is used and the system is cooled directly with air, but the costs are very high. New thermal power plant technologies are under development and have a potential to reduce the water consumption.

The water needed for power station cooling towers is running out in many parts of the world, for example in south-western USA, in South Africa and in China. Most of China's coal reserves are in the dry west. The World Resources Institute found in 2013 that more than 50% of planned future coal power stations in China were in provinces with 'extremely high water stress', for example Inner Mongolia, Shanxi, Shaanxi, Ganshu, Ningxia and Hebei.

13.6 MORE TO READ

Data from EU is available in EEA (2009). DOE/NETL (2010) and World Energy Council (WEC, 2010a) are key sources for water use and consumption for cooling. Wolfe *et al.* (2003)

give an overview of cooling water technologies. Stillwell *et al*. (2011) have analysed the consequences of using different cooling technologies in river basins in Texas.

There are several descriptions on Youtube on cooling systems (search for ‘cooling reactors’). In particular the causes of the Fukushima Daiichi disaster are described by the French institute IRSN (Institute de Radioprotection Researche et de Sûreté Nucléaire) on www.youtube.com/watch?v=JMaEjEWL6PU.

14

Water management in industry

The reality is that in much industrialized societies we are addicted to comfort.

Water is of prime importance for the industrial sector as it is used in a variety of ways for transport, cooling and heating, cleaning, washing and also as raw material. Major water using and/or discharging industries include the pulp and paper, textile, leather, oil/gas, chemical/pharmaceutical, food, energy and metal industries. The industrial sector is of great economic importance, where water related costs can reach up to 25% of the total production costs. The perspective has to be that water for the industry is not a consumable or utility anymore, but a highly valuable asset: a vital element used in close conjunction with production processes. As the second largest water user, industries have to develop these technologies to save and treat this critical factor.

It is obvious that water management in industry is the topic for a book for each one of the industrial sectors. Here we will focus on some clusters of industries having similar challenges. For example, cooling is an important part of many industries.

It is quite apparent that

> energy efficiency leads to water efficiency.

Water savings can of course be primarily obtained in an industry, but using energy more efficiently leads to indirect savings of water in the energy production processes. Measures to reduce the environmental impact usually have a direct financial payback. The issue often arises of cost-benefit and the economic efficiency of any technique can provide information for assessing the cost-benefit.

Within EU a Directive on industrial emissions was adopted in 2007, called the IPPC Directive (Integrated Pollution Prevention and Control). The IPPC Directive has been in place for a number of years earlier but the new Directive replaced seven existing Directives into one legislative instrument. The European IPPC Bureau was founded to organize the necessary exchange of information and to produce Best Available Techniques (BAT). A number of Best Available Techniques Reference Documents (BREFs) are available (http://eippcb.jrc.ec.europa.eu/reference). In this chapter we will refer to some of these documents.

In the US the Environmental Protection Agency has corresponding instruments, for example the Spill Prevention, Control and Countermeasure Rule (SPCC), particularly for oil pollution. Another one is WaterSense, an EPA program designed to encourage water efficiency in the US on consumer products. A third one is the webpage on *Industry sector notebooks*, further described in 14.7. Industrial cooling systems are discussed in 14.1. Water issues in the food, drink and milk (FDM) industries are considered in 14.2. Process control is a key technology, not only in industrial processes but in most energy systems. Some basic concepts are discussed in 14.3. The iron and steel industry is considered in 14.4 and the paper and pulp industry is briefly described in 14.5. The chapter is summarized in 14.6 and some further reading is suggested in 14.7.

14.1 INDUSTRIAL COOLING SYSTEMS

Cooling systems are required in many industries, not only in the power industry, as described in Chapter 13. Cooling is needed to remove excess heat from any medium, using heat exchange with water and/or air to bring down the temperature of that medium towards ambient levels.

The efficient use of energy in industrial processes is very important from environmental and cost-efficiency points of view. Using the best available technology (BAT) means that attention must be paid to the overall energy efficiency of the industrial or manufacturing process.

Distinction is made between low level (10–25°C), medium level (25–60°C) and high level (60°C) non-recoverable heat. In general, wet cooling systems are applied for low level heat and dry cooling systems for high level heat. For the medium level different configurations can be found.

The exchange of heat between process medium and coolant is enhanced by heat exchangers. From the heat exchangers the coolant transports the heat into the environment. In open systems the coolant is in contact with the environment. In closed systems the coolant or process medium circulates inside tubes or coils and is not in open contact with the environment. Closed circuit wet systems are widely used in industry for smaller capacities. The principle of dry air-cooling can be found in smaller industrial as well as in large power plant applications in those situations where sufficient water is not available or water is very expensive.

14.1.1 Energy consumption

The specific direct and indirect consumption of energy is an important environmental aspect relevant for all cooling systems. The specific indirect energy consumption is the energy consumption of the process to be cooled. This indirect energy consumption can increase due to a sub-optimal cooling performance of the applied cooling configuration, which may result in a temperature rise of the process (ΔK) and is typically expressed in $kW_e/MW_{th}/K$.

A cooling system typically consumes electrical energy in order to cool a thermal process.

The specific direct energy consumption of a cooling system is expressed in kW_e/MW_{th} and refers to the amount of (electrical) energy consumed by all energy consuming equipment (pumps, fans) of the cooling system for each (thermal) MW_{th} it dissipates. Typically, a change from once-through to recirculating cooling means an increase in energy consumption for auxiliaries, as well as a decrease of efficiency in the thermal cycle (similar to cooling in thermal power plants, Chapter 13). Pumps and fans with high efficiency must be used. Resistance and pressure drops in the process can be reduced by a proper design of the cooling system. Proper mechanical or chemical cleaning of surfaces will maintain low resistance in the process during operation.

Recovery of heat from industrial cooling waters using a heat exchanger can offer significant energy savings. This heat can either be used onsite for industrial processes and heating buildings or else exchanged and taken off site. Some European cities already have district heating networks (DHN) that provide both energy and carbon emissions savings. In Copenhagen, for instance, DHN supplies 97% of the city's heat needs (2009), with 80% of this heat recovered from electricity generating stations. This saves 655,000 tonnes of CO_2 annually (Thornton, 2009).

14.1.2 Water

Water is important for wet cooling systems as the predominant coolant, but also as the receiving environment for cooling water discharge. Discharge of large amounts of warm water can influence the aquatic environment, but the impact can be controlled by suitable location of intake and outfall.

Consumption of water can vary between 0.5 m^3/MWh_{th} for an open hybrid tower and up to more than 100 m^3/MWh_{th} for an open once-through system (compare Table 13.3). Reduction of large water intakes by once-through systems requires a change towards recirculating cooling. At the same time it will reduce the discharge of large amounts of warm cooling water and may also reduce emissions of chemicals and waste. The water consumption of recirculating systems can be reduced by increasing the number of cycles. Hybrid cooling, which allows dry cooling during some periods of the year, with a lower cooling demand or with low air temperatures can reduce water consumption in particular for small cell-type units.

Emissions into the surface water from cooling systems are caused by:

- applied cooling water additives and their reactants;
- airborne substances entering through a cooling tower;
- corrosion products caused by corrosion of the cooling systems' equipment; and
- leakage of process chemicals (product) and their reaction products.

Cooling systems may require the treatment of cooling water against corrosion of the equipment, scaling and micro-and macrofouling. Treatments are different for open once-through and recirculating cooling systems. For the latter systems, cooling water treatment programmes can be highly complex. To handle corrosion and scaling zinc, molybdates, silicates (Si_xO_y), phosphonates, polyphosphonates, polyol esters, natural organics, and polymers are applied. As a consequence, emission levels in the blowdown of these systems also show large variations and representative emission levels are difficult to report. Sometimes the blowdown is treated before discharge. Open once-through systems are predominantly treated with oxidizing biocides against macrofouling. Emissions of oxidizing biocides in open once-through systems, measured as free oxidant (FO) at the outlet, vary between 0.1 and 0.5 mg FO/l depending on the pattern and frequency of dosage. The use of halogens as oxidative additives in once-through systems will lead to environmental loads primarily by producing halogenated by-products.

A good practice is of course to reduce harmful effects of cooling water discharge. The blowdown should be treated before discharge into the receiving surface water. If the blowdown is treated in a wastewater treatment facility the remaining biocidal activity must be monitored as it may affect the microbial population. Detailed information is found in the comprehensive report EU (2001).

14.2 FOOD, DRINK AND MILK INDUSTRIES

The most significant environmental issues associated with the food, drink and milk (FDM) industries are water consumption and contamination, energy consumption, and waste minimization. The comprehensive report (EU, 2006) gives a detailed description of Best Available Technology in the FDM industries. Most of the water which is not used as an ingredient ultimately appears in the wastewater stream. Typically, untreated FDM wastewater is high in both COD and BOD. Levels can be 10–100 times higher than in domestic wastewater. The suspended solids (SS) concentration varies from negligible to as high as 120,000 mg/l. Untreated wastewater from some sectors, for example meat, fish, dairy and vegetable oil production, contains high concentrations of fats, oils and greases. High levels of phosphorus can also occur, particularly where large quantities of phosphoric acid are used in the process, for example for vegetable oil de-gumming, or in cleaning.

The FDM sector is an extremely diverse sector and a large user of water as an ingredient, cleaning agent, means of conveyance and feed to utility systems. Water in the FDM sector has many different uses:

- cooling and cleaning;
- raw material, especially for the drinks industry;
- process water, for example for washing and steeping of raw materials, and products;
- cooking, dissolving and transportation;
- auxiliary water, for example for the production of vapour and vacuum;
- cooling water.

About two thirds of the total fresh water used is of drinking water quality. In some sectors, for example dairies and drinks, up to 98% of the fresh water used is of drinking water quality. Process heating uses approximately 29% of the total energy used in the European FDM sector. Process cooling and refrigeration account for about 16% of the total energy used.

The quality of water needed depends on the specific use. The water use in the FDM industry in Germany can illustrate the situation. In 1998 the total industrial water consumption was 8500 million m^3 of which 300 million m^3 (3.5%) was used by the FDM sector. Nevertheless, the actual amount of water used in the FDM sector in that period was reported to be 1730 million m^3 (48% as cooling water and 25% as process water), that is more than the total consumption figure. This is because of recycled and reused water. On average, the number of times water was reused in the German FDM sector increased from 3.4 times to 4.2 times between 1995 and 1998.

The BOD_5 content of the main FDM constituents and some products is shown in Table 14.1. Wastewater from, for example the meat and dairy sectors contain high concentrations of edible fats and oils. Wastewaters contain few compounds that individually have an adverse effect on wastewater treatment plants or receiving waters. Possible exceptions include:

- salt where large amounts are used, for example pickling and cheesemaking;
- pesticide residues not readily degraded during treatment;
- residues from the use of chemical disinfection techniques;
- some cleaning products.

Table 14.1 BOD_5 equivalent of general FDM constituents and some products.

BOD_5 content
0.65 kg/kg carbohydrate
0.89 kg/kg fat
1.03 kg/kg protein
0.07–0.10 kg/l milk
0.18–0.37 kg/kg meat
0.06–0.09 kg/kg fruit or vegetables

Source: EU (2006).

Table 14.2 shows a summary of reported water consumption and wastewater volumes for some of the FDM sectors. As noted, there is a wide variation in the water consumption depending on the processes and the size of the installation.

Table 14.2 Summary of water consumption and wastewater volumes for some of the FDM sectors.

Sector	Water consumption	Wastewater volume
Meat and poultry	2–20 m^3/t	10–25 m^3/t
Fish	3.5–32 m^3/t	2–40 m^3/t
Fruit and vegetables	2.4–11 m^3/t	11–23 m^3/t
Milk and yoghurt	0.6–4.1 liter/liter	
	0.8–25 m^3/t	0.9–25 m^3/t
Cheese	1.2–3.8 liter/liter	
	1–60 m^3/t	0.7–60 m^3/t
Soft and alcoholic drinks	6–14 liter/liter	0.8–3.6 liter/liter

Source: EU (2006), Table 3.9.

14.3 PROCESS CONTROL

Process control is a key technology not only in all the various process industries. The basic task is simply to keep the plant operating. By more specific and advanced control an increased volume of the saleable product, improved quality and reduced waste can be obtained. Improving the process control of inputs, process operating conditions, handling, storage and wastewater generation can minimise waste by reducing off-specification product, spoilage, loss to drain, overfilling of vessels, water use and other losses.

The primary process control structures look quite similar in most of the process industries and includes conventional control loops for:

- *Temperature*: storage vessels, processing vessels and transfer lines. Possible benefits from this include reduced deterioration of materials, reduced out-of-specification products and less biological contamination.
- *Pressure*: pressure sensors are often used for the indirect control of other parameters, such as flow or level.

- *Level*: to keep levels at a certain value or to detect low or high levels. Flow rate control: allows the accurate addition of materials to storage and processing vessels and filling packaging, thereby minimising the excessive use of materials and the formation of out-of-specification products.
- *pH*: pH control is important in many applications, both in the chemical industry, FDM and the water industry.
- *Conductivity*: this is used to determine the purity of water or the concentration of acid or alkali.
- *Binary sensors* such as photocells can be fitted to detect the presence of materials and to supply water.
- *Automatic water start and stop*: Water should only be turned on when it is required. Water supplies should be turned off automatically between products and during all production stoppages.

The water and energy nexus will motivate integrated planning and operation not only for the individual unit processes but also on a plant wide level. The reason is that energy, steam and water are mostly common and shared resources for the whole plant. This requires coordinated control and operation. Instrumentation, control and automation are tools to apply to synchronize the various processes in a plant for better efficiency and resilience to disturbances.

The challenge of automation is to comprehend the system aspects from a unit process perspective and to understand the process aspects from a system perspective. One important consequence is that process specialists have to be able to appreciate the implications of control and automation. Likewise computer and control engineers have to understand the process controllability and its constraints. To consider the process operations from a water-energy perspective is a great challenge.

14.4 IRON AND STEEL

The most important environmental issues of iron and steelmaking relate to emissions to air and to solid wastes and by-products. Wastewater emissions from coke oven plants, blast furnaces and basic oxygen furnaces are the most relevant emissions to water in this sector. Both water and energy create interdependencies between the various processes in an integrated steel work. The almost 600 page draft report EU (2011) gives a comprehensive background for this Section.

To get a feeling for the water management we consider an integrated steel works with surplus of intake water availability, Table 14.3. This allows many once-through cooling systems, resulting in a specific water consumption of more than 100 m^3/ton steel. At sites with very low fresh water availability there is a need to save water as much as possible. In such cases the specific water consumption can be less than 10 m^3/ton steel, and sometimes less than 5 m^3/ton steel, in which case the interdependencies are much more intensive.

Energy forms complex interdependencies. The dominant energy inputs are coal and coke, but electricity, natural gas, and oil also represent the energy inputs. Around 88% of the imported energy is ultimately derived from coal, 83% of which is converted into coke. Blast furnaces consume about 60% of the overall energy demand of the steelworks, followed by rolling mills (~25%), sinter plants (~9%) and coke ovens (~7%).

Table 14.3 Example for the water management of an integrated steelworks at a location with high surplus of water availability.

Process	% once-through cooling	% waste-water treatment	% recirculation	Process description
Coke oven plant	88.8	2.4	8.8	Coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. It is there to reduce the iron oxide in order to collect iron. Since smoke-producing constituents are driven off during the coking of coal, coke forms a desirable fuel for stoves and furnaces. Coke may be burned with little or no smoke under combustion conditions, while bituminous coal would produce much smoke.
Sinter strand	9.8	0.8	89.4	Sintering is the agglomeration of fine-grained iron ores for blast furnace burden preparation.
Blast furnaces	70–74	1.5–12	18–25	This is the main operational unit in the steel works and is used to produce industrial metals, generally iron.
Hot rolling mill	11.6	22.2	66.2	Rolling is a metal forming process in which metal stock is passed through a pair of rolls. The process is termed ‘hot rolling’ if the temperature of the metal is above its recrystallization temperature.
Cold rolling mill	99.7	0.3	0	If the temperature is lower, then the process is termed ‘cold rolling’.
Strip coating	94.1	5.9	0	A process used to protect the steel strip surface.

Data Source: EU (2011).

14.5 PAPER AND PULP

Paper is essentially made of fibres that are combined with certain chemicals to form a sheet of desired quality. On top of these key ingredients the paper and pulp processes require a large amount of water and energy in the form of steam and electrical power. The main environmental issues in the paper and pulp industry are emissions to water and to air as well as electric energy consumption. In regions with a well-developed paper and pulp industry the emissions to water and air have typically been reduced by 80–90% or more on a specific basis since about 1980. There is a development to further close up the water circuits in the paper and pulp processes and a further reduction of discharges can be expected, toward the effluent free mills.

The *bleach plant* was earlier the great polluter, mainly due to the use of chlorinated substances. The chlorine bleaching was causing great contamination of the receiving waters. Today there are severe restrictions in many countries of using molecular chlorine as a bleaching chemical and it has been replaced by chlorine dioxide (ClO_2) and introduction of other oxygen-containing chemicals such as molecular oxygen (O_2), peroxide (a compound containing an oxygen–oxygen single bond ($[O{-}O]^{2-}$) and ozone (O_3). Due to the strong reduction of the chloride content of the effluents a closure of the mill system and recycling of the bleach plant effluent back to the chemical recovery system of the mill has been made possible.

The *sulphate* (containing SO_4^{2-}) or *kraft process* is the dominating pulping process worldwide due to the superior pulp strength properties and its applications to all wood species. Emissions to water are dominated by organic substances. Best available technologies regarding water includes recycling of process water from the bleaching process and collection and reuse of clean cooling waters. For chemical pulping no external energy is needed but the total demand on process energy is still high.

The *sulphite* (containing SO_3^{2-}) *process* is used much less than the kraft process. In many respects the sulphite and sulphate processes are similar, in particular regarding possibilities to reduce emissions to the environment. The main differences are in the chemistry of the cooking process, the chemical recovery system and the amount of bleaching required. The sulphite pulp has a better initial brightness.

In *mechanical pulping* the wood fibres are separated from each other by mechanical energy applied to the wood matrix. This is the most energy-intensive process because of the electricity demand of the refiners. The characteristics of the pulp can be influenced by increasing the process temperature. The wood can also be pre-treated by chemicals to become softer and then refined under pressure. Such a process is called *chemo-thermo mechanical pulping* (CTMP). In the best available techniques water recirculation is implemented in the mechanical pulping department. White water (a general term for all waters of a paper mill that have got separated from the pulp suspension) from the paper machine is often recycled to the mechanical pulp mill.

Recovered fibre processes use recycled paper as the fibre raw material, which is much more economically favourable than virgin pulp. The paper is used for packaging paper, newsprint, or tissue paper. There are two main categories of recovered fibre processes:

- Processes with only mechanical cleaning and no de-inking. The products are used for corrugated medium, board or carton board.
- Processes with both mechanical and chemical cleaning, resulting in de-inking. These products are used for newsprint, printing and copy paper, tissues and so on.

Recovered paper processing includes energy-intensive processes. A number of water related good practices can be used, such as:

- Separation of contaminated water from less polluted water;
- Recycling of process water;

- Treatment of de-inking water (sedimentation, flocculation, biological treatment) and recycling of process water.

A lot of energy is needed for the *paper making*. Electric power is needed to supply all the motor drives. Process steam is consumed in the dryer section of the paper machine. For the paper making a dilute solution of around 5% fibres has to be brought to about 95% dry solids content in the finished paper product by means of pressing and drying – and this involves evaporation of water. Large quantities of water are used as process water. A good practice is to recirculate process water and to treat and recirculate the white water.

Table 14.4 shows the water flow of various processes in the paper and pulp industry. The water emissions are also documented as BOD, COD, suspended solids, and AOX (adsorbable organic halides, a measure of organically bound chlorine compounds).

Table 14.4 Water flows – yearly averages – of various paper and pulp processes (cooling water and other clean waters are discharged separately).

Process		Flow m³/Adt[a]
Kraft process	Bleached pulp	30–50
	Unbleached pulp	15–25
Sulphite process	Bleached pulp	40–55
CTMP mill	Pulping only	15–20
Recovered fibre process	Without de-inking	<7
	With de-inking	8–15
Paper machine		10–15[b]

[a] Adt = air dry tonne of pulp (dry solids content 90%)
[b] m^3 per ton of paper
Source: EU (2013), various tables

The energy issue is also critical. A Swedish pulp mill discovered that at 850 kWh per pulp ton its energy consumption was far too high. The plant had oversized motors for the pulp pumping. Changing the motors to variable speed (see Chapter 16.1 and 22.1) reduced the energy consumption to 645 kWh per pulp ton. The annual savings are huge, around 134 GWh (www.abb.com/motors&drives).

14.6 CHAPTER SUMMARY

Energy and water are key ingredients in a large number of industries. Again, it is apparent that saving energy means saving water and vice versa. Best available technologies have been developed in many industrial sectors, but still a lot of development remains. The work with 'end-of-pipe' treatment of contaminated water should be moved upstream in order to make the primary processes more efficient, thus making some of the down-stream treatment unnecessary.

14.7 MORE TO READ

It is outside the scope of this book to describe details of process control and there is a huge literature on this topic. A couple of books with a profile on chemical process control are recommended: Seborg *et al.* (2010) and Marlin (2000). The book by Stephanopoulos (1984) is regarded a standard text book. Olsson-Newell (1999) considers particularly control of wastewater treatment systems.

Li-Nwokoli (2010) have analysed the water footprint for the packaging industry.

The U.S. EPA maintains a webpage called ‘Industry sector notebooks’, http://www.epa.gov/compliance/resources/publications/assistance/sectors/notebooks/ (latest access 13 Dec. 2014) that contains a wealth of environmental information for various industrial sectors, such as Profiles for:

- the Agricultural Chemical, Pesticide and Fertilizer Industry, 2000;
- the Agricultural Crop Production Industry, 2000;
- the Agricultural Livestock Production Industry, 2000;
- the Fossil Fuel Electric Power Generation Industry, 1997;
- the Inorganic Chemical Industry, 1995;
- the Iron and Steel Industry, 1995;
- the Metal Mining Industry, 1995;
- the Oil and Gas Extraction Industry, 2000;
- the Petroleum Refining Industry, 1995;
- the Pulp and Paper Industry, 2002;
- the Water Transportation Industry, 1997.

PART IV

Energy for water

Even for the non-expert it is apparent that the whole cycle of water transport, treatment, consumption, and collection and treatment of wastewater depends on energy. Around 2–3% of the world energy is used for water supply and sanitation purposes. There is significant room for the reduction of energy consumption. In industrialized countries, energy is the second highest cost after labour costs in the water and wastewater industry. However, it should also be realized that the energy consumption at the end user (consumer) of water significantly exceeds the energy used in the rest of the urban water cycle.

The consumption of electrical energy can be compensated by the recovery of energy from the water and wastewater. The organic content of wastewater can be used to produce biogas, which in turn can generate both heat energy and electrical energy. The heat content of water can be extracted for heating buildings and processes and can also be used for cooling as an environmentally friendly air conditioning.

Water is a valuable finite natural resource and wastewater is a source of beneficial compounds. The goal is to ensure that the water demands of natural systems are environmentally balanced with people's domestic and commercial needs. We should view our wastewater treatment systems not just as 'end of the pipe' works, but as resource recovery plants, capturing biogas, and utilizing nutrients, fats, oils, and grease in wastewater as valuable sources.

Chapter 15 gives an overview of the energy needs in water and wastewater operations. Actually, all wastewater treatment works have the potential to become energy neutral and large plants (>100,000 persons) can become energy positive. Pumping (Chapter 16) and aeration (Chapter 17) can be made more energy efficient, biogas can be produced more efficiently (Chapter 18), and the thermal energy content can be utilized (Chapter 19). The energy requirement of desalination is discussed in Chapter 20. Finally, the demand side, our behaviour, life-style and habits, has a crucial influence on the energy requirement of the water cycle (Chapter 21).

15 Energy and carbon footprint of water operations

> *Do you want free energy? Perpetuum mobile, unbelievable machine that produces labor from 'nothing' is patented and scientifically proved.*
>
> 'Innovation' on the Internet.

This chapter provides an overview of the energy need for various water operations. Later chapters in part Four will consider the potential for energy savings or recovery in different operations. Saving water also means that:

- less energy is needed for the production and distribution of drinking water;
- less energy is used by the consumer (e.g. heating of water). The water user has a significant impact on the availability of both water and energy;
- less energy is needed for the collection and treatment of wastewater.

15.1 DIFFERENT FORMS OF ENERGY

The basic SI unit of energy is *joule* (see Appendix 1). Today we know that heat is a form of energy. We are all familiar with that mechanical energy can be changed completely into heat and that the conservation-of-energy principle is valid. For example, the kinetic energy of a moving car is changed completely into heat in the braking system when we brake the car to a halt. The reverse process – changing heat into work – is another matter. If heat could be changed completely into work, then the heat content of the water in a biological reactor could be used to supply the compressors with electrical power for the aeration.

15.1.1 Converting energy

The direction of which natural events happen is governed by the **second law of thermodynamics**. There are several formulations of the law. One is that it is *not possible to change heat completely into work*, with no other change taking place. Another way to say this is that there are *no 'perfect' engines*. That is, no real engine can have an efficiency of 100%.

It is not possible to change heat completely into work.

Heat flows naturally from a hot place to a cool place. There is never any 'natural' net heat flow from cool to hot. This observation can be expressed in an alternative formulation of the second law of thermodynamics: it is *not possible for heat to flow from one body to another* *body at a higher temperature*, with no other change taking place. Alternatively this means that *there are no 'perfect' refrigerators*. Sometimes the second law of thermodynamics is expressed like 'nature hates differences'. The energy tries to spread around until there are no more differences in temperature. So, even if energy cannot get lost according to the first law of thermodynamics expensive chemical energy in oil and coal will be transformed to less useful heat energy.

A **heat pump** is a device that – acting as a refrigerator – can be used to extract heat for example from the effluent water of a wastewater treatment plant, do some work, and discharge the heat for example in a district heating system. The maximum (theoretical) performance of the heat pump depends only on the temperatures of the two reservoirs between which it operates. The coefficient of performance (COP) is given by

$$\text{COP} = \frac{T_C}{T_H - T_C}$$

where T_C is the temperature of the cold reservoir and T_H the temperature of the warm reservoir, so for a small temperature difference there is a large COP and for a large difference we get a small COP. The COP indicates how much electrical power that is needed to add in order to operate the heat pump. This means that a heat pump with COP = 4 needs a supply of 1 kWh of electric energy in order to produce 4 kWh of heat.

15.1.2 Exergy – quality of energy

It is because of the irreversible nature of many energy processes that the concept of exergy has been defined. The exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. In other words, exergy is the energy that is available to be used. The term was named in 1956 by Zoran Rant but the concept was already developed by J. Willard Gibbs in 1873. Exergy, like energy is expressed in joules. Certain forms of energy such as kinetic energy, electrical energy and Gibb's free energy are 100% recoverable as work, and therefore their exergy is the same as the energy. However, forms of energy such as radiation and heat energy cannot be converted completely to work and have an exergy content that is less than the energy content. Obviously 1 kWh of electrical energy has a higher exergy value than 1 kWh of heat. The exact proportion of exergy in a substance depends on the amount of entropy relative to the surrounding environment as determined by the second law of thermodynamics. Some examples of exergy values are given in Table 15.1.

Table 15.1 Examples of exergy values.

Form of energy	Exergy/energy (%)
Electrical energy	100
Chemical energy	≅100
Hot steam (200°C)	≅70
District heating water	≅70
Heat content of wastewater (15°C)	<5

Source: Lingsten *et al.* (2009).

Exergy = maximum useful energy

15.1.3 Example of useful energy

300 kg of steam at 400°C at 4 MPa (40 bar) and 6 tonnes of water at 40°C contain the same amount of energy (assuming the same reference temperature), namely 1 GJ. The steam at 4 MPa can achieve useful work (via equipment), such as generating electricity, moving mechanical equipment, heating, and so on, but there is a limited use for water at 40°C. The exergy of the low temperature water can be raised but this requires expenditure of energy, such as using a heat pump.

The second law of thermodynamics teaches us the important lesson that we have to be careful to compare different forms of energy production and consumption. To simply add all energy forms is a mistake. It is nothing else than to calculate the cash balance by simply counting the number of dollar bills without noting if they are 1 or 20 dollar bills.

15.1.4 Energy in a wastewater treatment plant

A lot of energy is entering a typical wastewater treatment plant via the influent load. The water contains thermal energy that can be used. Wastewater from municipal users as well as from industry usually has a lot of excess heat. Primarily this will make the biological reactions in the plant more efficient, since the biological reaction rates are much depending on the temperature. Still the effluent water will have excess heat that can be recovered. The influent also contains chemical energy in terms of organic content. This can be extracted as biogas (Chapter 18). External electrical energy has to be supplied to the pumps, compressors and other equipment that runs the plant. Also, chemicals are added for different purposes, for phosphorous removal using chemical precipitation, for supplying a carbon source in denitrification processes, or for dewatering sludge. It is quite natural that the process should be operated in such a way that the external input of electrical energy and chemical energy is minimized, while the energy output in terms of biogas or thermal energy should be maximized.

15.2 ISO STANDARD

In Chapter 9.1 we presented the new ISO standard to estimate water footprint. An international standard for energy management, ISO 50001, was released in June 2011. The standard itself does not establish energy goals for organizations, but it helps them to develop effective management policies and procedures to improve energy efficiency. This includes planning, implementation, monitoring and corrective actions. Energy efficiency is of fundamental importance for the water industry, so the interest for the new standard seems to be very high. Considering the fact that energy generation consumes large amounts of water (see Part Three and Chapter 9.1) makes improvements in energy efficiency more imperative. Among the more than 19,000 ISO standards defined over 150 of them are related to energy efficiency and renewables. Some examples are:

- ISO 14001 and ISO 50001 promote good practice in environmental and energy management;
- ISO 14064–1:2009 and 14065:2013 are devoted to greenhouse gases and requirements for greenhouse gas validation and verification.

There are several subcommittees (SC) and technical committees (TC) working with specific topics and standards, for example ISO/TC 180/SC1, working on climate and measurements and data, such as specification and classification of instruments and calibration methods. The ISO/TC 238 works specifically with solid biofuels.

15.3 ENERGY USE FOR WATER OPERATIONS

As water resources become scarce, water may end up being pumped long distances, or being produced through energy consuming alternative means, such as desalination processes. Here we will summarize the energy requirement for the different phases of water supply and wastewater treatment.

> More water consumption and more advanced treatment will usually lead to bigger energy use. This in turn will require more water for the energy production.

15.3.1 Water operations – national levels

On a national level the electrical energy consumption for water and wastewater operations is in general quite small. The European Union average electrical energy consumption was in 2009 around 6,700 kWh/year/person, which corresponds to the average electrical power of 760 W/person. The typical power level in European wastewater treatment works corresponds to only around 1% of the national consumption, or 7–8 W/person. It may be argued that energy savings in the wastewater industry cannot solve the global energy crisis. This may be true, but the energy cost for the water operations is an increasing and significant part of the operating costs.

Wastewater treatment electrical power in Europe corresponds to 7–8 W/person.

A rough estimate of the energy requirement to produce clean water is given in Table 15.2. More data on desalination is presented in Chapter 20.

Table 15.2 The energy cost to produce clean water.

Type of water supply	Energy footprint of water supply and treatment (kWh/m^3)[a]	
Surface water	0.5–4	0.37
Groundwater		0.48
Reused water	1–6	1–2.5
Desalination	4–8	2.6–8.5
Bottled water	1000–4000	

[a] See Appendix 1 (A1.9) for conversion of units.

Sources: WssTP (2011b), first column; WBCSD (2009b) and Scientific American, Oct. 2008, second column.

Nowak *et al.* (2011) describe self-sufficient wastewater treatment operations. Making wastewater treatment more sustainable is discussed for example by Sutton *et al.* (2011) and by McCann (2007). Frijns *et al.* (2010) have investigated best practices of wastewater treatment operations in more than 25 plants.

Most water companies in Europe utilize only 1% of the total national electricity usage and represent some 0.4% of the carbon footprint (Caffoor, 2008). However, some water companies in UK report increases of over 60% in electricity usage since privatization due to advanced treatment and increased connection rates. Conservative estimates predict increases of a further 60–100% over the next 15 years (after, 2008) in order to meet new EU Directives. UK data reveals that energy typically represents 28% of operating costs of water industry operations, with aeration representing 55% of sewage treatment operations and pumping representing 60% of water treatment operations. Energy use to generate 1 m^3 of clean water (average) in the UK requires 0.59 kWh and generates 0.29 kg of greenhouse gases (Caffoor, 2008).

In the US drinking water and wastewater systems account for approximately 3–4% of energy use (EPA, 2013).

In Australia the water sector uses about 1.4% of all electrical energy. Energy consumptions for Australian plants are shown by Hartley (2013). Data from the 15 largest utilities in Australia in 1998 show that for water supply the energy use varied between 1.3 kWh/m^3 down to 0.08 kWh/m^3 with the median value around 0.27 kWh/m^3. The median energy consumption for wastewater treatment was 0.33 kWh/m^3, while the maximum value was 0.80 and the lowest among the 15 utilities was 0.085 kWh/m^3.

Kenway *et al.* (2008) provide an interesting comparison between the energy use for water supply and wastewater treatment for a number of Australian cities, Table 15.3. The data is from 2006–2007. There is a factor of more than 20 between the energy minimum and maximum for water supply. It can be noted that Melbourne has the water supply close to the city, while Adelaide has to pump its water a long distance. The pumping energy is of the same order of magnitude as the energy required for desalination. For the wastewater treatment there is a factor of 2.5 between the highest and the lowest energy requirement. An important difference is the degree of wastewater treatment. For example, in Sydney most of the wastewater is only treated with primary treatment before discharged into the ocean (in, 2014 88% of the wastewater has only primary treatment). Melbourne is using secondary and tertiary wastewater treatment and then has to pump the effluent water over higher terrain before ocean disposal.

Table 15.3 Energy use in some cities in Australia and New Zealand.

City	Water supply kWh/m^3	Wastewater treatment kWh/m^3
Sydney	1.0	0.45
Melbourne	0.09	1.1
Brisbane	0.68	0.57
Gold Coast	0.21	1.0
Perth	0.98	0.71
Adelaide	1.9	0.69
Auckland	0.21	0.84

Source: Kenway *et al.* (2008), Table 2.

The European Environment Agency (EEA) has led a project concerning sharing knowledge bases to support environmental and resource efficiency policies and technical improvements (see Jacobsen, 2014). It is obvious that energy consumption for drinking water production and distribution depends to a high degree on the source water quality as well as distance for transport and elevation for pumping, so a high variation is expected. Based on data from 85 utilities serving a population of 2.2 million people the energy consumption for water supply in Germany is reported in Jacobsen (2014). The aggregated weighted mean values from this benchmarking for the energy consumption are 0.5–0.7 kWh/m^3 (authorized consumption). The ranges from the 90 percentile are anywhere from 0.06 and 1.1 kWh/m^3. Data from 57 utilities in Denmark serving a population of around 3 million reveal energy consumption of 0.3–0.6 kWh/m^3. Swedish data from 181 utilities serving a total of 6.6 million customers show higher values of 0.93 kWh/m^3 (authorised consumption). A weighted mean value from these data is 0.76 kWh/m^3 (authorised consumption) (Jacobsen, 2014).

Taking a wider European perspective there is benchmark data from 31 large water utilities across geographical Europe serving about 71 million people. The average energy consumption for water supply is then given to 0.5 kWh/m^3. This energy consumption includes possible distribution losses.

Wastewater treatment (sanitation) also requires a lot of energy. Again this is site specific. The energy to collect the wastewater and to pump it to the wastewater treatment facility depends of course on the geography and the topography. The energy for the wastewater treatment also depends on the type of process, plant size, wastewater composition and temperature, to mention a few parameters.

A review by Zhou *et al.* (2013) compares the current wastewater treatment technologies and how they are applied around the world. In particular the consequence for energy reduction and recovery are considered. In Canada the energy consumption wastewater treatment with no nitrogen removal was found to be 0.305 kWh/m^3 compared to the nitrifying case of 0.405 kWh/m^3. Brandt *et al.* (2011) have studied global best practices covering the water cycle matrix. The paper includes variations between regions and continents, large urban and small rural systems and complex high and simple low technical solutions.

To measure the energy use in water and wastewater treatment it is important to relate it to adequate key performance indicators (KPI). In Table 15.4 some KPIs are suggested.

Table 15.4 Suggested key performance indicators for water operations.

Energy use and energy production	
Energy requirement (kWh) per m^3 of water	**Heat production (MWh/year)**
Total	Extraction of heat content in the effluent water
Pumping water supply	Biogas production
Pumping of raw wastewater	Produced volume
Aeration	Internal heat production
Mixing	Electric Power production
	Purchase of heat energy
Energy use for wastewater treatment (kWh/kg)	**Chemical use**
Removed nitrogen	
Removed BOD	Phosphorous removed (g) per chemical use (g)
Removed COD	

The specific electricity consumptions for sanitation are typically around 35–40 kWh/year/person (Jacobsen, 2014). However, Sweden has a weighted mean of 95 kWh/year/person, while the weighted mean for the German, Danish and Swedish datasets is 43 kWh/year/person. One important factor to explain the differences is that Germany and Denmark are so much more densely populated than Sweden.

The differences in electric power consumption of municipal WWTPs in Japan have been evaluated by Mizuta-Shimada (2010). Meda-Cornel (2010) present data on energy use for water operations and make comparisons between Australia, Germany and California. Novotny (2011) and Hofman *et al.* (2011) have analysed how water and energy are linked to the development of the city of the future.

15.3.2 Pumping

Pumping is a crucial operation in all kinds of water and wastewater transport and treatment. It will be further discussed in Chapter 16.1. The power P_{hydr} (W) to lift water H(m) can be expressed as:

$$P_{\text{hydr}} = Q \cdot H \cdot \rho \cdot g \qquad (15.1 = 16.5)$$

where Q = flow rate (m^3/s), H = head (m), ρ = density (kg/m^3), and g = acceleration of gravity (=9.81 m/s^2).

EXAMPLE

To lift water with a flow rate of 10 liters/second from a depth of 30 m will require a *power* of $P_{\text{hydr}} = 0.01 \cdot 30 \cdot 1000 \cdot 9.81$ W = 2943 W = 2.95 kW. Assuming that the pump/motor efficiency is 50% the electric power required will be 5.9 kW. The *energy* needed to lift 1 m^3 of water from the 30 m depth then is 5.9*100/3600 = 0.16 kWh.

Pumping water from the source to the water treatment works is vastly different from one region to another. To pump groundwater will usually require more energy than to pump from a surface water source. Some US data indicate that the energy need to pump groundwater is anywhere between 0.14 and 0.60 kWh/m^3 (Griffiths-Sattenspiel & Wilson, 2009). From the pump equation (15.1) we find that the average groundwater depths are anywhere between 25 m and 110 m. Pumping groundwater in the Central Valley of California requires at an average 0.60 kWh/m^3 of water. This indicates that the groundwater levels are alarmingly low.

The energy to pump the water from the source to the water treatment depends on the distance and the topography that can be very different. California presents an extreme example of water pumping costs, as shown in Table 15.5. Southern California is a dry area and the water has to be pumped long distances. To deliver water from Northern to Southern California the water has to be lifted over the more than 600 m high Tehachapi Mountains. Also in a dry area like Adelaide the pump costs are high. Johannesburg in South Africa is located at an altitude of 1750 m above sea level, which explains the high pumping costs for the city.

Water pumping costs are vastly different from one region to another.

Table 15.5 Examples of raw water pumping energy.

From source to waterworks	kWh/m³[a]
Sweden average	0.24
Sweden low–high	0.04–0.64
Melbourne, Australia	0.09
Adelaide, Australia	1.9
Northern California	0.04
Southern California	2.3
California low – high	≅0–4.2
Johannesburg, South Africa	1.37
Cape Town, South Africa	0.17

[a]See Appendix 1 (A1.9) for conversion of units.
Sources: Lingsten *et al.* (2008), Kenway *et al.* (2008), DOE (2006), Table III-1, Rabe (2008), Clarke-King (2006).

Griffiths-Sattenspiel and Wilson (2009) indicate the energy need for water supply and conveyance (US) anywhere between 0 and 3.7 kWh/m^3.

Pumping represents up to 90% of energy consumption for clean water and up to 30% for waste water processes (Brandt *et al.* 2011). The authors claim that:

- There is potential for between 5% and 10% improvement on existing pump performance;
- There is potential for between 3% and 7% improvement on pump technology;
- Simple gains are possible in some pumping situations where the operational set up has been changed from the design condition. Gains of between 5% and 30% may be realized.

15.3.3 Drinking water treatment

The energy – almost exclusively electrical energy – consumption for water supply is seldom recorded in the water statistics. Some national water utility associations maintain statistics on energy consumption by the water sector. To supply 1 m^3 of drinking water (pumping + water treatment) requires:

- *UK*: 0.59 kWh (Caffoor, 2008);
- *Netherlands* 0.47 kWh/m^3 (with 0.16 kWh/m^3 coming from renewable energy sources). This includes total energy consumption of drinking water supply; raw water intake, treatment and distribution. This corresponds to 2.6 W/person (Hofman *et al.* 2011)
- *Sweden*: 0.24 kWh for pumping (average) and 0.12 kWh for water treatment. The distribution of energy consumption is large, as shown from Swedish statistics (Lingsten *et al.* 2008, see Table 15.6).
- *US*: in the range 0.025–4.2 kWh/m^3 (Griffiths-Sattenspiel & Wilson, 2009);
- *Australia*: from 0.03 to 0.6 kWh/m^3 of water (Apostolidis, 2010).

It should be remarked that the interest in using renewable energy sources, such as solar energy, for remote areas is increasing. Ultraviolet (UV) radiation of 60 W can be used to kill bacteria and viruses via DNA disruption. A single solar panel (or wind energy or low-head hydro) can power such a system, which is capable of disinfecting about 20 liters/minute. Even less energy will be needed in the future for UV disinfection of contaminated water as UV LEDs become available, where the emitted radiation is narrowly focused on biologically active UV wavelengths. Solar powered small pumping systems are also applied in rural areas.

Table 15.6 Electric energy consumption in 37 water works in Sweden with more than 2000 persons connected.

	Electric energy for the water treatment process (kWh/m^3)	Electric energy for pumping (kWh/m^3)
National average	0.12	0.24
Minimum	0.01	0.04
Median	0.16	0.22
Maximum	0.72	0.64

Source: Lingsten *et al.* (2008), Tables 3.3, 3.4, 4.3.

15.3.4 Water distribution

Electrical energy has to be used to supply the pressure for water distribution systems. Swedish figures may represent typical electrical energy use for water distribution and are retrieved from Lingsten *et al.* (2008), Tables 3.1, 3.6, 4.4. The annual energy use is around 10.4 kWh/person. However, there is a great variation of the energy requirement, depending on topography and population density, from 1.4 to 38 kWh/person with the median value 8 kWh/person. Considering that all the waterworks deliver an average 110–114 m^3/capita/year the average energy consumption for the water distribution is calculated to be close to 0.10 kWh/m^3. Corresponding distribution energy in Australia is reported between 0.3 and 0.5 kWh/m^3 (Apostolidis, 2010). UN WWDR (2014, Figure 2.3) report values between 0.05 and 0.24 kWh/m^3.

15.3.5 Wastewater collection and pumping

Most of the energy used for collection and transportation of wastewater is for pumping. In Sweden the average pumping energy is 20 kWh/capita/year (Table 4.9 in Lingsten *et al.* 2008). The variation, however, is very large, from 1 to 89 kWh/capita/year with the median value 29, which indicates that the energy need is site specific. It has to be remembered that the pumping energy depends to a large extent on the rain volumes. The incoming water to the wastewater treatment plants corresponds to 313 m^3/capita/year in Sweden. Consequently the energy for the transport of sewage water is close to 0.06 kWh/m^3.

- Australian energy requirements are reported in the range 0.01–0.5 kWh/m^3 (Apostolidis, 2010).
- US data are in the range 0.18–1.2 kWh/m^3 (Griffiths-Sattenspiel & Wilson, 2009);

15.3.6 Wastewater treatment

Wastewater treatment, sludge treatment and disposal require electrical power. Pumping and aeration in biological treatment processes are the dominating energy users. Statistics for wastewater generation, collection and treatment as well as sludge generation and disposal are maintained by OECD and Eurostat and also by UN for different sectors. The EEA report Jacobsen (2014) presents a comprehensive European perspective.

Primary treatment of wastewater is sometimes called mechanical treatment. Pollutants are removed by sedimentation or filters and the solids are removed by scrapers.

Biological nutrient removal (BNR) is a term used to describe plants that employ biological processes to remove organic matter (C) as well as nitrogen (N) and phosphorous (P) components. This involves microorganisms feeding on the nutrients and the oxygen in the water. Electrical energy is used to supply the biological reactor with compressed air that becomes available for the microorganisms as dissolved oxygen. This is further discussed in Chapter 17. This means that the aerator has to be controlled so that it balances between the biological need for oxygen and the energy cost to supply the air. Table 15.7 gives some Australian figures to illustrate the variability. Typically aeration in the biological treatment systems represents around 50% of the wastewater operating costs.

Table 15.7 Energy requirement for wastewater treatment in Australia.

Type of operation	kWh/m^3 (min,max)	kWh/m^3 (average)
Primary	0.1–0.37	0.22
Biological C removal (incl. primary)	0.26–0.82	0.46
Advanced C, N and P removal	0.39–11	0.90

Sources: Kenway *et al.* (2008); Sydney Water; Brisbane Water.

The energy intensity of treating wastewater depends not only on the level of treatment but also of the size of the plant. Table 15.8 presents some US data.

Table 15.8 Energy requirement for wastewater treatment in the US.

Size of plant	Electrical energy consumption (kWh/m^3)		
m^3/s	MGD[a]	Activated sludge biological C removal	Activated sludge with nitrification
0.044	1	0.59–0.69	0.78
0.44	10	0.32–0.37	0.47
4.38	100	0.27–0.31	0.41

[a] Million gallons per day

Source: Griffiths-Sattenspiel and Wilson, (2009), Table 2.3.

The Strass wastewater treatment plant in Austria, performing C removal and nitrification, can serve as a role model, as it uses 0.35 kWh/m^3.

Energy requirements for wastewater collection and treatment:

- *in California*: 0.3–1.2 kWh/m^3 (DOE, 2006, Table III-1) and,
- *in the UK*: 0.63 kWh/m^3 (Caffoor, 2008).

Energy for wastewater treatment has to relate to the pollutants removed and not only to the water volume.

To relate the energy use to the volume of water only tells part of the truth. As indicated in Table 15.4 it is important to relate the energy consumption to the amount of organic components, nitrogen as well as phosphorus removed. Usually it is difficult to find reliable data for energy consumption related to the wastewater load. There is a significant difference between the energy requirements for different wastewater treatment plants, as illustrated by Table 15.3 for Australian cities. The differences are due to plant size, the type of load (for example industrial or mainly domestic) and the type of operation. In Sweden the energy requirement for wastewater operations varies from 1.5 to 40 kWh per kg BOD (organic carbon removal), with a median value of 4.5 kWh. Figure 15.1 summarizes the energy requirements of the urban water cycle.

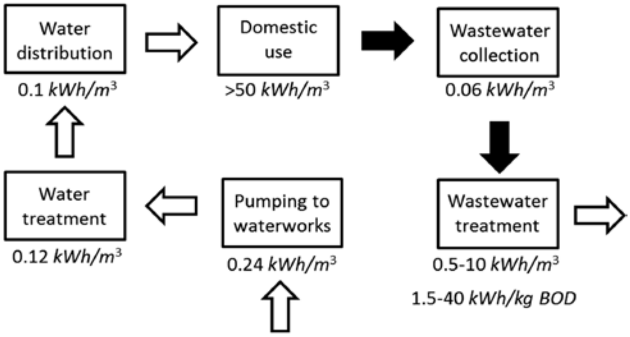


Figure 15.1 The urban water cycle and its energy footprint. (*Source:* Swedish data from Lingsten *et al.* (2008)).

15.3.7 Household end use

Most often the energy used by the water and wastewater operators is discussed while the end user energy use is forgotten or neglected. The amount of energy used in handling the water in the household is significantly greater than the energy used by the water operators. Water heating will require around 50 kWh/m^3 which is an order of magnitude larger than the energy for water delivery and wastewater treatment. According to statistics (Reffold *et al.* 2008) around 90% of the energy related to the water cycle is consumed 'at home'. This is further discussed in 21.3.

If the end use of water is taken into consideration the energy consumption in the water cycle is significantly higher than reported by the utility statistics. Then the energy for water is 10–20 times higher. For example, in California 19% of the electricity is spent on water, where most of the energy is spent by the end-user (Cohen *et al.* 2004). The two dominant energy sources for heating water in the US are natural gas (50%) and electricity (40%) (Griffiths-Sattenspiel & Wilson, 2009).

It is important to consider the energy source for water heating. For example, it is much less energy-intensive to heat water by direct use of natural gas on-site than to heat the water via electric power that has been generated via the natural gas. The power plants will have large conversion losses as discussed in Chapter 13. Of course solar thermal heating systems are much better from a greenhouse gas point of view.

15.4 GREENHOUSE GAS EMISSION FROM WASTEWATER OPERATIONS

The electrical energy used for the various water and wastewater operations is of course a source of CO_2 emission. There are additional operations that directly contribute to greenhouse gas emission. Methane (CH_4) emission appears in sewers, and nitrous oxide (N_2O) is a byproduct in biological treatment of nitrogen compounds. Furthermore, greenhouse gases are emitted when untreated wastewater and sludge are discharged into the environment.

15.4.1 Methane emission in sewers

Methane emission in sewers has got the attention, since it can make up 20% or more of the overall GHG emission in wastewater treatment. Methane generation in sewers will reduce the organic content (measured in COD, chemical oxygen demand) which will influence the nutrient removal performance in the wastewater treatment plant. Furthermore this COD reduction decreases the energy content of the wastewater that potentially can be used in the more controlled biogas production in anaerobic treatment. Still the knowledge of the mechanisms of the methane production in sewers is quite limited, but a lot of research is on-going.

Guisasola *et al.* (2008) and Foley *et al.* (2009) analyse methane formation in sewers. Models have been derived for CH_4 emissions in pressurized sewer systems (Guisasola *et al.* 2009) and research is ongoing to derive emission models for gravity systems. Liu *et al.* (2014, 2015) report new results on on-line monitoring of methane in sewer systems.

15.4.2 Nitrous oxide emission in activated sludge systems

Nitrous oxide (N_2O) is a powerful greenhouse gas, as described in Chapter 4. It is generated during biological wastewater treatment. Consequently the operation of the plant should try to minimize the emission of N_2O to the atmosphere. The global N_2O emissions from wastewater treatment have been estimated at 4.8% of the total anthropogenic emissions and 2% of the total N_2O emissions.

Wastewater treatment plants are mostly subject to highly variable loads, and consequently the emissions of N_2O are varying significantly as part of the total nitrogen load. The emissions are associated with the nitrification and denitrification processes.

Both nitrifying and denitrifying biomass can produce N_2O. Nitrous oxide accumulation mechanisms by nitrifying microorganisms are not well known. So far mostly N_2O production by denitrifying microorganisms has been considered. In the denitrification process heterotrophic microorganisms work under oxygen free (anoxic) conditions and reduce nitrate (NO_3^-) to nitrogen gas (N_2). The process contains four steps and nitrous oxide (N_2O) is an intermediate product in one of the steps. An incomplete denitrification can produce N_2O emissions. For example, limitation in organic content can lead to incomplete denitrification and the subsequent N_2O production.

Kampschreur *et al.* (2008, 2009, 2010) document greenhouse gas emissions from wastewater treatment and also discuss the balance between energy efficiency and greenhouse gas emissions. Guo *et al.* (2012) have proposed a benchmark simulation model, which includes a wastewater treatment plant wide model and a rising main sewer model, for testing mitigation strategies to reduce the system's greenhouse gas (GHG) emissions.

15.5 ENERGY SAVINGS

We can consider energy savings and efficiency improvements from three angles of attack:

- *Water savings*: by saving water we will save energy. This can be done through waste minimization and recycling in industry (Chapter 14), by leakage reduction (Chapter 16.2), and by savings and recycling at home (Chapters 21 and 22);
- *Improving efficiency in water operations: There are two principal possibilities*: retrofitting the equipment and/or using control and automation. In the latter case one also has to consider the investment in instrumentation, actuators (such as controllable pumps and compressors) and computer control systems. See further Chapters 16–20;
- *Using the resources of the wastewater*: extracting heat content (Chapter 19), nutrients and producing biogas (Chapter 18).

In some countries there is already a requirement to decrease the energy use for water and wastewater operations. In California a 20% increase in energy efficiency will be required according to the California Water Plan Update 2009. In China the Central Government will require at least a 20% decrease in energy use and in Sweden a new energy savings program is being implemented where the goal is to save at least 20–30% in electrical energy requirement for wastewater treatment operations. In Germany the Ruhrverband has managed an ambitious energy savings program (Thöle, 2008).

> *Energy is saved by saving water. Energy can be recovered from water. Energy efficiency can be raised by control and automation.*

According to the Global Water Research Coalition it is quite feasible to obtain an energy consumption reduction by 20% by optimisation and innovation. The existing systems in the water and wastewater industry haven't reached the limits of improvement of its energy efficiency yet. GWRC also argues that a further reduction of the energy consumption with another 80% should be possible, but this requires a paradigm shift. The current water infrastructures have been designed and constructed on the basis of views, requirements, conditions and technologies of decades ago. It is recognised that in the present systems wastewater treatment, water treatment and distribution are very energy intensive. New concepts could include topics like alternative sanitation approaches (separation at the source); from waste towards resource (P and N recovery; wastewater as nutrient for algal based biofuel); microbial fuels cells; tailored water quality; and use of alternative resources and so on. The water and wastewater sector could benefit from technology developments and breakthrough in related areas like energy production, sensor development, and nanotechnology.

According to WssTP (2011b) there is a great need for development of sensor, monitoring and communication technologies:

- Economical, reliable and maintenance-free sensors;
- Sensors and communication systems for monitoring of assets condition and operation (such as nano-sensors inside the materials and in the close soil);
- On-line monitoring of water quality and of treatment processes:
  - at individual level (domestic, 'small' systems);
  - for collective systems.

A best practice can be developed in terms of instrumentation, control and automation (ICA) that can lead to improved process control, decision support tools, and smart remote metering systems. All of this can lead to efficiency improvement by energy and other resource savings.

New and improved processes offer great savings, such as improved methods for disinfection, sludge destruction, low energy desalination. More efficient pumping and low friction pipes will further contribute to significant energy savings.

Many control systems are focusing on individual unit processes. A plant-wide perspective has to be developed, as pointed out in Chapter 14.3. We have emphasized several times the importance of integrated decisions. The complexity of environmental problems makes it necessary to develop new tools capable of processing not only numerical information but also non-numerical criteria and experiences from experts and wide public participation. All of this is needed in decision making, as discussed in Chapter 10.5. Environmental decision support systems have been developed during the last decade and are most promising to confront this complexity.

15.6 FROM WASTEWATER TREATMENT TO RESOURCE RECOVERY

Until now we have been too much occupied with treating the water at the end of the pipe. The concept of wastewater treatment is gradually changing to the concept of both energy and nutrient recovery. The challenge is not only to satisfy the effluent criteria, but also to evaluate the potential for energy use on-site and for energy production. There is an obvious potential to save energy by more efficient pumping, aeration, mixing and other operations in wastewater treatment. Monitoring, control and automation is part of that solution. The energy potential in the organic content can be used as biogas. This will in turn be an energy source to supply the treatment plant with both heating and electrical energy (Chapter 18).

15.6.1 Biogas

It has been noted that there is an important overcapacity of anaerobic digester volumes (for biogas production) in municipal wastewater treatment plants in some countries, notably in countries like Germany and Sweden, anywhere from 20% to 50% available extra volumes. It is safe to assume that the same situation is true in many other countries. Furthermore, by reducing the hydraulic retention time in the anaerobic digesters only slightly – by using better instrumentation, monitoring and control – the throughput can be further increased. Using these extra resources to digest additional substrates with high energy content as biogas can make a wastewater treatment plant not only energy independent but also make it a net energy producer (see further Chapter 18.4).

Wastewater treatment plants should be nothing else than resource recovery plants.

15.6.2 Resource recovery

The water also contains nutrients that should be recovered; in particular phosphorous (P) that is a limited resource. However, methods for P recovery are outside the scope of the book. The goal of the 'new' plant is also to reduce the greenhouse gas emissions.

The city of Amsterdam has already come a long way to extract energy from the water cycle. The city has set the emission target to a 40% reduction of CO_2 emissions as compared to 1990 levels. Targeting towards sustainable energy the city has already made use of biomass on a large scale. Furthermore, using the heat content of surface water, groundwater as well as wastewater a lot of thermal energy can be used both for heating and for cooling (see Chapter 19).

The concept of the city of the future has got a lot of attention lately. Water and energy will play a major role in the creation of the sustainable city. This will include not only renewable energy sources, such as solar and wind, but also energy extracted from used water and stormwater, water conservation and reuse, storage of runoff from precipitation as well as energy recovery via biogas. These aspects will be further discussed in the following chapters.

To obtain energy savings in water, energy consumption must be measured. Some advices to water utilities from Rabe (2008) are worth citing. On the theme *Think water and energy and global climate change* he stated:

- 'To measure is to know – start measuring!
- Once you have started measuring, then start monitoring;
- Go after the quick-wins – they are out there!
- Think efficiency before thinking expansion;
- Start simple but recognize that creating efficiencies is actually a complex task. Nothing kills a new initiative more effectively than complexity.'

15.7 CHAPTER SUMMARY

It is important to distinguish between different forms of energy when considering energy balances. In a national perspective the electrical energy used for water operations is small, of the order 1–3%. However, energy costs for the operation of water and wastewater systems are significant and increasing. It is possible to make most plants energy self-sufficient and even as net producers of energy, if the resources in terms of organic content, nutrients and heat are properly recovered. Control and automation can improve the energy efficiency significantly. The end user energy use in relation to water is an order of magnitude larger than the water and wastewater transport and treatment. Energy savings will be obtained via water savings. Our attitudes to wastewater should be changed. It is nothing less than a resource in energy and in nutrients. Thus, wastewater treatment should be resource recovery.

15.8 MORE TO READ

Grady *et al.* (2011) provide a comprehensive basis for the understanding of biological wastewater treatment.

The UN report WWAP (2011) contains energy data for water and Eurostat (epp.eurostat.ec.europa.eu) provides comprehensive databases for environment and energy. U.S. energy requirements are discussed in Southwest Hydrology (2007) and in EPA (2010b).

There are increasing numbers of publications concerning energy requirements and efficiency in water operations. In particular the journals Water Science and Technology and Journal of Water and Climate Change give the energy issues an increasing attention. The book by Brandt *et al.* (2012) contains many practical examples how to increase the efficiency in the water industry. The paper by Sharma *et al*. (2011) presents full scale experiments on energy savings in aeration basins.

Instrumentation, control and automation (ICA) are essential tools to save energy and keep the operation consistent at all times. There is a vast literature on this topic. Recent surveys of the ICA developments are found in Olsson (2012b) and Olsson *et al*. (2014) as well as the textbook Olsson-Newell (1999) and the state-of-the-art report Olsson *et al*. (2005). Olsson (2008) presents an introduction of process control in wastewater treatment.

Poch *et al*. (2004) and the position paper McIntosh *et al*. (2011) describe the interesting development of decision support systems for environmental problems.

16 Pumping water

> *A body remains in a state of rest or … motion unless acted upon by an external force.*
>
> Sir Isaac Newton, Principia Mathematica, 1687.

Transporting water – clean or contaminated – is a key operation. Pumping represents upwards of 80% of clean water and at least 30% for waste water energy demand. The water has to be moved from the source – a river, lake or aquifer – to some kind of treatment. Water distribution again means pumping and using energy. Transporting the contaminated water from the user to the treatment is often realized by gravity transportation, but sooner or later the water has to be lifted to a wastewater treatment plant for further treatment. Within the treatment plant water has to be moved around between various unit processes. It is apparent that pumping technology is an essential component of any water system, and having efficient pumping is crucial for any operation.

A lot of water is lost in distribution systems due to leaking. Lost water means lost energy. Globally there are enormous amounts of both water and energy that are lost due to inadequate piping. We will discuss not only the importance of quality piping but also of methods to automatically detect and localize leakages in pressurized water pipe systems.

Sewers are not pressurized. Still they are leaking, but now the surrounding water will leak *into* the sewer pipe. As a result there will be more water for treatment. Again there is a high energy cost to treat all the extra water entering the system.

In the last section of the chapter we will consider pressure control in water distribution systems. There is a significant savings potential to control the pressure and allow it to vary, depending on the water consumption. Energy will be saved and as an extra bonus the leakage probability will decrease significantly.

16.1 PUMPING

There is sometimes a notion that water can be transported in the same way as oil, long distances. In principle this is true, but the transportation cost related to the cost of water is generally too high. Still drinking water is transported long distances in some places. Pumping water long distances and lifting the water across the mountains will cost a lot, as indicated in Table 15.5 so the energy cost for desalination of seawater no longer seems unrealistic (see Chapter 20).

Pumping is a major part of the cost to bring drinking water to the consumers and to move the wastewater from the consumer to the wastewater treatment plant. In the majority of cases, energy consumption is the largest cost in the life cycle costs of a pump system, where pumps often run more than 2000 hours per year. Actually, around 20% of the world's electrical energy consumption is used for pump systems.

To provide electrical energy for pumping in rural areas of developing countries is not obvious. However, interesting products based on solar energy are now available.

16.1.1 Bernoulli's law

In order to understand the basic operation and energy issues of pumping we will base the discussion on the law of energy conservation. Consider water flowing in a single pipeline with only one intake and one discharge and without any energy input or output. The Bernoulli equation (named after the mathematician Daniel Bernoulli, who published his principle in 1738) expresses all the energy of the water in terms of *head*, which is typically expressed as meters of water. This is energy per unit weight. The Bernoulli equation states that the sum of velocity head (v), pressure head (p) and elevation head (z) at any point is the same as the corresponding sum at any other point, adjusted for head loss (H_L) between the two points:

$$\frac{v_1^2}{2g} + \frac{p_1}{\rho g} + z_1 = \frac{v_2^2}{2g} + \frac{p_2}{\rho g} + z_2 + H_L \tag{16.1}$$

where ρ is the liquid density and g the acceleration of gravity. The first term is the kinetic energy per unit mass (M):

$$\frac{Mv^2}{2Mg} = \frac{v^2}{2g} \tag{16.2}$$

which has the dimension *meter (m)*, since the velocity v is given in *m/s* and the acceleration of gravity g in *m/s*^{2}. The second term in (16.1) is the *pressure head* (often called the *static pressure*) at the point of measurement. It represents the static head above or suction head below the point of measurement plus any induced pressure from valve closure. The pressure is measured in Pascal (*Pa*) (*N/m*^{2}) and the liquid density ρ in *kg/m*^{3}, so the second term also has the dimension *m*. The term z is the elevation head in *m*, and the *head loss* H_L refers to frictional losses. The *dynamic* pressure is measured in *Pa* and is defined as:

$$p_{dyn} = \frac{\rho v^2}{2} \tag{16.3}$$

where ρ is the liquid density (*kg/m*^{3}) and v the velocity (*m/s*).

EXAMPLE

If the velocity of a water flow is 5 *m/s*, the dynamic pressure is $p_{\text{dyn}} = 1000 \cdot 5^2/2 = 12500$ *Pa* ≅ 0.13 *bar*, which is considered insignificant in many pumping systems.

16.1.2 Pump performance curves

The most common pump type is the *centrifugal pump*, where the pump principle is to convert mechanical energy from the motor to velocity energy in the pumped medium, the water. This will create a pressure difference in the media between the pump inlet and outlet. We will discuss the basic characteristics of pump performance curves but will disregard details on pump construction and pump types.

Let us first consider the load characteristics, also called the *system characteristics*. The pump has to create a pressure that drives the liquid flow through the pipe. According to the

Bernoulli equation the pressure consists of both *static* and *dynamic* pressures. The system characteristics look like Figure 16.1. The static pressure appears at zero flow rate. In the figure there are two different cases represented with two different elevations. If the friction losses in the pipe are small then the slope of the characteristics is small. Conversely, if the losses are high, then the characteristic is steeper. The dynamic pressure and the friction losses depend on the square of the water velocity v, in other words on the square of the flow rate Q.

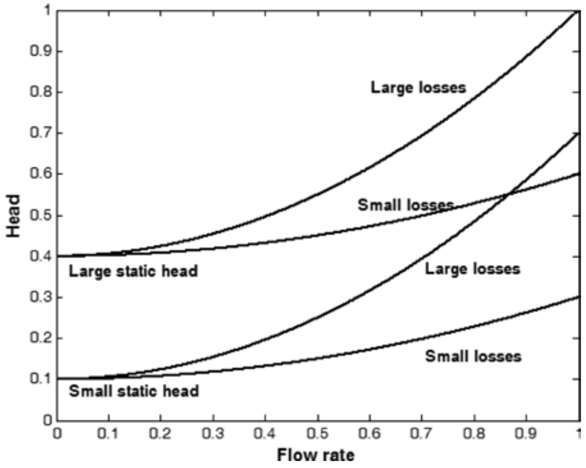


Figure 16.1 Different system curves that represent the load to the pump.

> *The system characteristics describe the pressure that the pump has to produce to drive the flow.*

A pump performance is defined by its *pump characteristics*, the QH curve, Figure 16.2. The curve shows the head, which the pump is able to perform at a given flow. Head is measured in meter liquid column (*mLC*). The advantage of using the unit *m* as the unit of measurement for a pump's head is that the QH-curve is not affected by the type of liquid the pump has to handle. The relation between the head (H, in m) and the pressure (p, in $Pa = N/m^2$) is

$$H = \frac{p}{\rho \cdot g} \tag{16.4}$$

where ρ is the liquid density (kg/m^3), and g the acceleration of gravity (m/s^2). According to (16.4), pumping at a pressure of 1 *bar* (=10^5 *Pa*) corresponds to a water column ($\rho = 1000$) of 10.2 *m*.

> *The pump curve relates the pressure that a pump can produce as function of the flow rate.*

If the rotational speed (n) of the pump is changed then the QH curve is changed according to Figure 16.2. A lower speed means that the pump produces a lower head at a given flow rate, or produces a lower flow rate, given the head. If the pump is aimed to work at only one given head and flow rate then the slope of the QH curve has no importance. However, normally in a wastewater treatment plant the flow rate is highly variable. Therefore one has to consider the relationship between flow rate, pressure and efficiency.

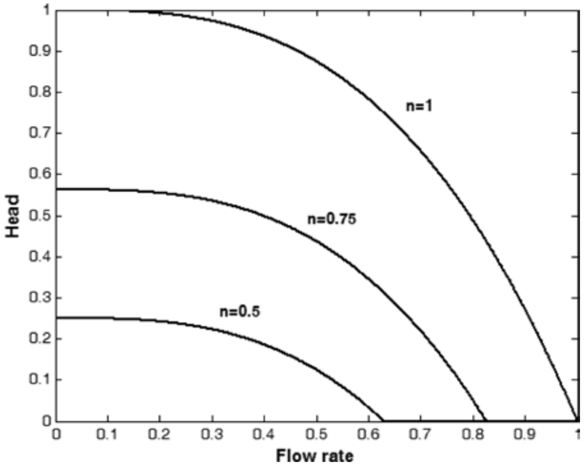


Figure 16.2 A typical pump characteristics or QH curve at different pump speeds (n).

The operating point (or *duty point*) of a pump is determined by the intersection of the pump (QH curve) and system characteristics, as shown in Figure 16.3. The QH curve defines what the pump can produce while the system curve (the load) defines which pressure is needed. The given duty point A is stable. This means that if the flow rate is getting lower than the duty point then the pump will deliver a pressure that is higher than what is required by the load. The pump will increase its speed and consequently the flow rate until it returns to the duty point. Similarly, if a disturbance will make the flow rate larger than the operating point, then the pump delivers a smaller pressure than is required. This will decrease the flow rate back to the operating point.

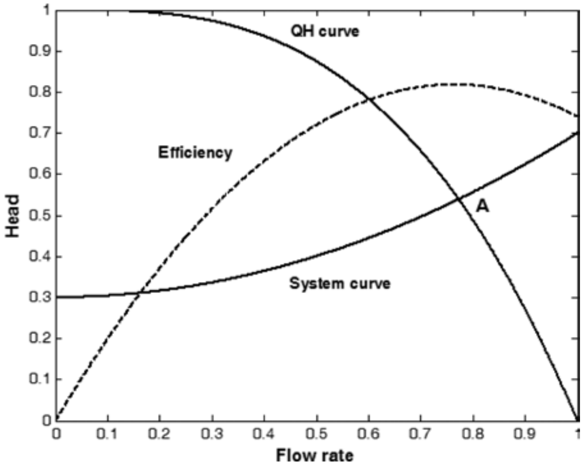


Figure 16.3 The duty point A of a pump is determined by the intersection of the QH curve and the system curve. The efficiency for a typical centrifugal pump is also shown.

16.1.3 Pump efficiency

When selecting a pump it is important to choose a pump where the duty point is within the high efficiency area, Figure 16.3. Here the pump losses have a minimum. In a system with variable flow it is of course impossible to operate the pump at the maximum efficiency point all the time. Then the pump has to be designed so that the most common flow rates are around the most efficient operating point of the pump.

The true pump duty point will almost always differ from the theoretical one. There are inaccuracies in the calculation of main losses, as well as error margins in the published pump performance curves. Furthermore, the pump characteristics will change with use due to wear and the dynamic pressure will increase with age due to corrosion or sedimentation.

The design of the impellers in the pump has a decisive influence on the QH curve. This will determine if the QH curve is steep or not. A pump with a steep QH curve will usually have a better efficiency. On the other hand, a pump with a not so steep QH curve will have a head that is less depending on the flow rate.

16.1.4 Changing the flow rate

There are two principal ways to decrease the flow rate:

- using a throttle valve, or
- changing the speed of the pump.

A throttle valve will increase the pressure in the pipe, creating a higher load to the pump. Thus, the system characteristic will be steeper, while the QH curve remains the same. According to Figure 16.4 the duty point will move from A to B, and a smaller flow rate will be produced at a higher pressure. Naturally this leads to higher energy losses. Note, that this is still a common way to control the flow rate in both liquids and gases because of its simplicity. However, the cost for the energy loss is going to be less and less tolerable. The desired flow rate could have been produced either with a smaller pump (a lower QH curve) or the same pump with a lower speed. Control by 'throttling' is like trying to control your car's speed by braking with one foot while continuing to accelerate with the other. Of course there is a waste of energy, but it also causes excessive wear and tear on equipment.

> *Variable speed control is superior to throttle valve control from an energy point of view.*

A pump with a variable speed motor drive will change the speed (n) to produce a lower flow rate, as illustrated in Figure 16.5. Now the system curve is unchanged and the QH curve is adjusted. The energy loss by throttling is avoided.

Consequently variable speed control by means of a frequency converter is a more efficient way of adjusting pump performance exposed to variable flow requirements. This simple approach can significantly reduce the amount of electricity a motor-pump system uses, and also lengthen the life of equipment that is no longer subjected to the jolting on/off braking that results from throttling. Variable speed control is also desirable from a process operation point of view. An on/off pump creates sudden hydraulic shocks. Firstly it causes pressure shocks that will wear the equipment. Secondly, and more important, hydraulic shocks are extremely detrimental to sedimentation processes and will cause a decreasing process performance.

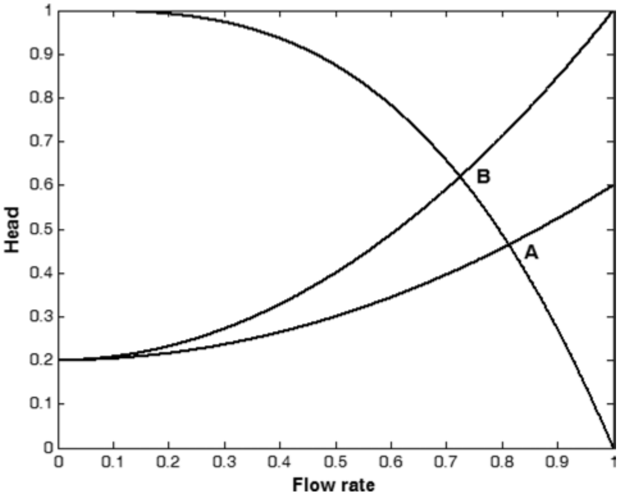


Figure 16.4 Controlling the flow rate with a throttle valve means that the system curve is made steeper. The duty point is moved from A to B, causing a lower flow rate at a higher pressure.

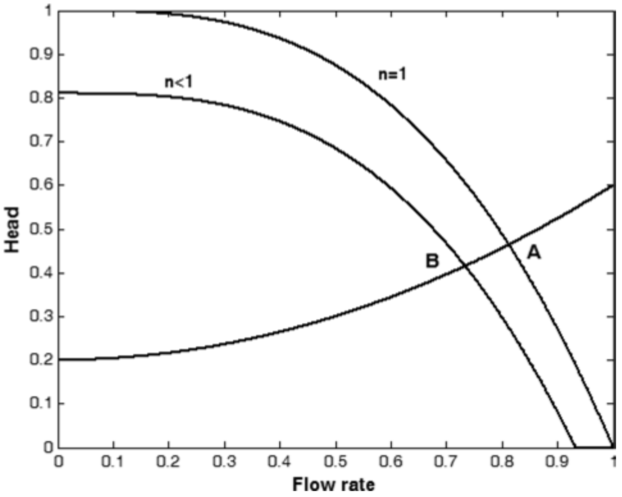


Figure 16.5 Controlling the flow rate with variable speed. The QH curve will change with the speed and the duty point is moved from A to B. A smaller flow rate is realized with a smaller head, causing minimal energy losses.

16.1.5 Pump losses

We consider three kinds of power related to pumping:

(i) The power delivered to the electrical motor connected to the pump is called the *incoming power* P_{in}, in other words, the electrical power that the consumer has to pay for.

(ii) The power transferred to the pump shaft is the *mechanical power* (the shaft power) P_{shaft} and is slightly smaller than the incoming power as a result of some small power losses in the motor. The rated power of a motor is the mechanical power at the normal operating point. Consequently the rated power is not the same as the consumed electrical power.

(iii) The mechanical power P_{shaft} is transferred to the *hydraulic power* P_{hydr} – the power that the pump transfers to the liquid in the shape of flow.

The mechanical power (expressed in *W*) can be calculated from:

$$P_{hydr} = Q \cdot H \cdot \rho \cdot g \qquad (16.5 = 15.1)$$

where Q = flow rate (m^3/s), H = head (m), ρ = density (kg/m^3), and g = acceleration of gravity (m/s^2). To get the *energy* (in *J*) the Q is replaced by the total volume V (m^3). The hydraulic power is proportional to the flow rate, so doubling the flow rate will require the double pump power. The power loss from the shaft power to the hydraulic power, $P_{shaft} - P_{hydr}$, defines the pump losses. The total efficiency for the pump is defined as:

$$\eta_{tot} = \frac{P_{hydr}}{P_{in}} \qquad (16.6)$$

Each pump is characterized by the relationship between flow rate and efficiency. Usually the efficiency has a maximum at a given flow rate, as illustrated in Figure 16.3. For typical pump units consisting of both pump and electric motor, the *total* efficiency η_{tot} also includes the efficiency of the motor and the frequency converter of a variable speed motor. For the most common pump types, the term *power rating* normally refers to the *shaft* power and is measured in *W* or *kW*.

EXAMPLE: PUMPING GROUNDWATER

Many groundwater sources are located several hundred meters below ground. The energy to pump 1 m^3 of water from a depth of 300 m will require (16.5) $1 \cdot 300 \cdot 1000 \cdot 9.81\ J = 2.94 \cdot 10^6\ J = 0.82\ kWh$. A pump having 80% efficiency would need 0.82/0.8 = 1.02 *kWh* electric energy.

16.1.6 The relationship between flow rate and power

In order to describe the relationship between flow rate, pump speed and power requirement for a pump we will briefly mention the *affinity laws*, illustrated in Figure 16.6. The pump flow rate is proportional to the pump speed n:

$$Q = \alpha \cdot n \qquad (16.7)$$

where α is a constant. In other words, if the speed is halved then the flow rate will be halved. The head H is proportional to the square of the speed n:

$$H = \beta \cdot n^2 \qquad (16.8)$$

where β is a constant. The power is very sensitive to the speed:

$$P = \gamma \cdot n^3 \qquad (16.9)$$

where γ is nearly constant. The power relationship tells that half the flow rate requires only around 1/8 of the power. In reality, the pump efficiency is different at different speeds and flow rates, so the practical relationship between P and n is not as dramatic. Still, the relation (16.9) explains why variable speed control is superior to throttle valve control from an energy point of view. In practice, a reduction of the speed will result in a slight decrease in efficiency. Therefore, to calculate more precisely how much power can be saved by reducing the pump speed one has to take the efficiency of the frequency converter and the motor into consideration.

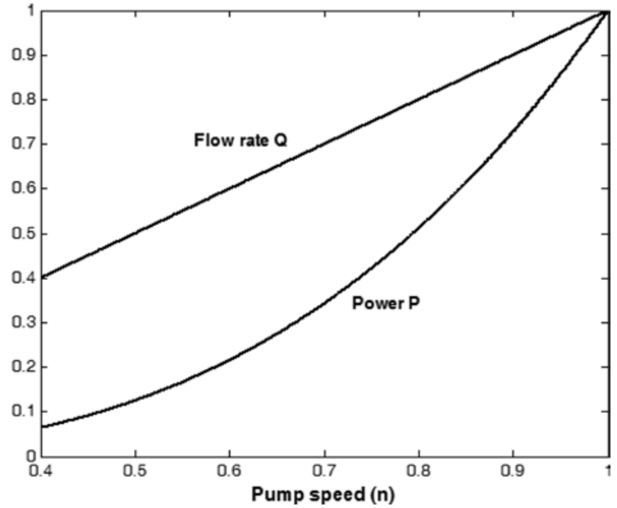


Figure 16.6 The relationship between flow rate and power requirement vs. speed, according to the affinity laws.

The power P depends on the cube of the pump speed (n^3).

EXAMPLE: ENERGY REQUIRED TO PUMP A GIVEN VOLUME OF WATER

Consider the energy (*kWh*) required to pump a certain volume of water. We will demonstrate this by pumping at full speed ($n = 1$) and with reduced speeds, as illustrated by Figure 16.7. The static head is zero, so the case can demonstrate recirculation pumping in a pre-denitrification wastewater treatment plant. The upper curve in Figure 16.7 depicts the volume of water being pumped. The slope of the curve corresponds to the flow rate (e.g. *liter/s*). At a full speed pumping ($n = 1$) the volume 1 has been pumped at time $t = 1$. At half speed, $n = 0.5$, it will take the double time to pump the same total volume. The lower curve of Figure 16.7 shows the consumed energy and the slope corresponds to the consumed power. To pump a given volume will take twice as much time when $n = 0.5$, but the consumed energy is only 25% of the used energy at full speed. The numbers obtained are only approximate, since we did not make accurate calculations of the losses, but it shows the potential of variable speed drives.

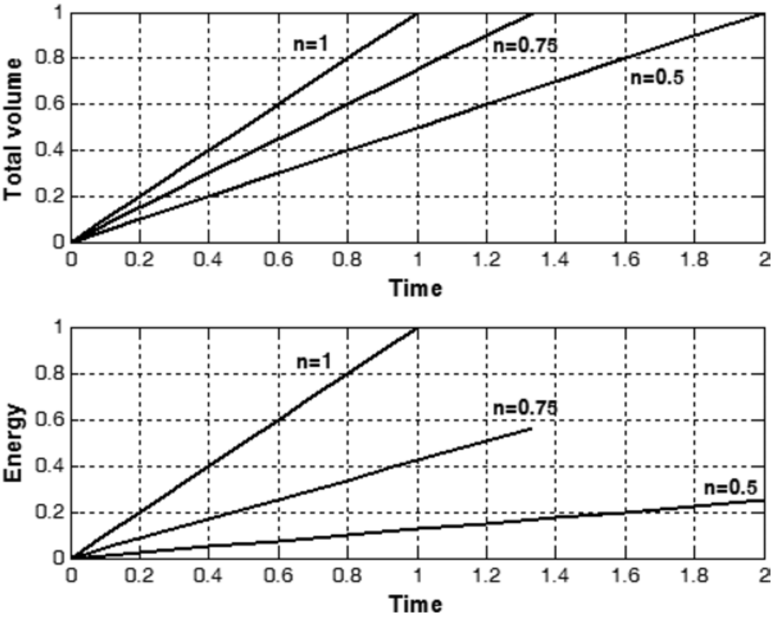


Figure 16.7 Pumping a given volume of water at different pump speeds. The upper curve shows that a given volume of water can be pumped in 1 time unit at full speed ($n = 1$) while 2 time units are required at half speed ($n = 0.5$). The lower curve demonstrates that 1 energy unit (e.g. 1 *kWh*) has been consumed at time 1 at full speed. Using half the speed ($n = 0.5$) it will take 2 time units to pump the same volume, and the required energy is 1/4.

EXAMPLE: ILLUSTRATION HOW TO CONSIDER THE TOTAL EFFICIENCY

A variable speed pump was operating satisfactorily but had too large maximum flow and operated at only 60% of its capacity. At this flow rate the efficiency was lower, only 65% for the motor + pump unit. A new pump with an adequate capacity was shown to have around 80% efficiency at the most common flow rate. Therefore it was profitable to get a new pump. Thus, it is important to understand that a poor efficiency cannot be compensated completely by variable speed control.

EXAMPLE: CONTROL OF INFLUENT FLOW PUMPING IN A WASTEWATER TREATMENT PLANT

Energy can be saved by a modified control of the influent flow pumping in a wastewater treatment plant. Two pumps were used in parallel for the influent flow pumping. For simplicity, assume that each one had the capacity 1 m^3/s and more than 1 m^3/s had to be pumped. The earlier strategy was to use one pump at maximum flow rate, while the second pump took care of the rest of the flow. For example, a flow rate of 1.3 m^3/s was split up as 1 + 0.3 m^3/s using two pumps. The modified strategy used was to let both pumps have the same flow rate, in this case 0.65 + 0.65 m^3/s. At these flow rates the efficiencies of the pumps are better. When

▶

the incoming flow rate was smaller than 0.5 m^3/s then one of the pumps was shut down. The efficiency could be further improved by investing in smaller pumps if small flow rates appear often.

We have seen that there is more than one way to influence the efficiency. Most often more than one pump is installed so as to achieve both better reliability and efficiency. If there are low flows quite often then it may be recommendable to install a small pump having the best efficiency at the low flow rates. Another pump can be designed to have the best efficiency at the most common flow rates. Then, for each flow rate it is possible to configure the best combination of pumps. For the cost-benefit analysis it is obvious that investment costs as well as operating costs have to be taken into account.

In some cases the head for the influent flow pumping can be modified. By changing the water level in the influent flow trunk sewer to a wastewater treatment plant the energy required to pump the water can be influenced. Such a modification does not require any investments.

EXAMPLE: SAVING ENERGY BY CHANGING THE WATER LEVEL

One example is from the Rya wastewater treatment plant in Göteborg, Sweden. An increase of 0.2 *m* of the average level in the trunk sewer means an energy saving of about 100,000 *kWh*/*year*. The negative consequence is that the buffer capacity in the trunk sewer will decrease by some 7% of the current capacity, and this requires a reliable flow control. Another negative consequence is that more particulate material will settle in the sewer. Sooner or later these sediments will be pumped to the treatment plant, sometimes at the 'wrong' occasion (Gryaab AB, 2007).

16.1.7 Friction losses in pipes

Friction losses in pipes will consume a significant amount of energy. This is of course true in any water, wastewater or process industry operation. The Darcy-Weisbach equation describes the relationship between the pressure loss h_f due to friction and a number of parameters. The equation states that the pressure loss (expressed in *m*) due to friction depends on the roughness f of the pipe surface, the length L of the pipe, the pipe diameter D and the velocity v of the water:

$$h_f = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \tag{16.10}$$

A typical friction factor f for a pipeline for water transportation is 0.01. The factor $v^2/2\,g$ denotes the dynamical pressure, obtained from the Bernoulli equation (16.1). The friction parameter f is also influenced by couplings, valves, bendings and corners as well as the input and output of the pipe. Every obstacle in the pipe will change the speed of the water and will require that the water is accelerated again. This will of course require energy.

The friction factor f is usually determined experimentally. The influence of the roughness of the surface is denoted by a parameter ε that depends on the pipe material. A small ε means a smooth surface. Typical values are $\varepsilon = 0.25$ for cast iron, $\varepsilon = 0.046$ for steel and $\varepsilon = 0.0015$ for plastic pipes, so the friction is about 30 times smaller in a plastic pipe compared to a steel pipe when no other local losses are considered. This also means that local losses from couplings and valves become a larger fraction of the total pressure losses in a plastic pipe (Bertin, 1987). This fact can cause new problems in a water supply pipe. Suppose that a section of cast iron pipe has been replaced by a plastic pipe. As a result the friction losses in the new pipe section have decreased considerably. With a given pressure at the distribution pumping it means that the pressure in the remaining cast iron pipe will be even larger. If there are cracks in this pipe the probability for increasing leakage will increase even more.

Local pressure losses can be significantly reduced by smooth corners instead of sharp ones, or gradual (conical) diameter changes instead of abrupt changes. A sharp 90° corner of a pipe will have 3–10 times larger losses than a corner with a larger radius *R*. The pressure losses will decrease with increasing *R*.

EXAMPLE: FRICTION LOSSES IN A PIPELINE (I)

Consider a pipeline of 400 *km* length, 0.5 *m* diameter and a flow velocity of 0.5 *m*/*s*. We assume $f = 0.01$. This will create friction losses $h_f \cong 100$ *m*. The power to compensate for this friction (Eq. 16.5) is ≅ 100 *kW*.

The pressure loss depends significantly on the pipe diameter. To illustrate this fact, just consider the continuity condition that states that the volume of water is constant before and after a cross area change:

$$A_1 \cdot v_1 = A_2 \cdot v_2 \tag{16.11}$$

where A_i is the cross section area and v_i the water velocity. This means that the pressure losses will decrease significantly when the diameter gets larger. A doubling of the diameter means that the velocity is only 1/4 and the factor v^2/D in the friction expression (16.10) will be only 1/32 of the previous value. Thus, the pressure losses due to friction will be only 3% of the previous value if the pipe diameter is doubled.

EXAMPLE: FRICTION LOSSES IN A PIPELINE (II)

In the pipeline example above, let us increase the diameter by 10% to 0.55 *m*. Then the flow velocity will decrease to 0.41 *m*/*s*. This results in friction losses h_f of only 62 *m*, that is, a decrease of 38% compared to the 0.5 *m* diameter pipeline. The required power for this friction is around 60 *kW*. However, it has to be emphasized overdesigned pipes may create other problems that will increase the total costs.

The Darcy-Weisbach equation can also describe how the friction relates to the flow rate Q. Since the water velocity is proportional to the flow rate the friction will increase as Q^2. Thus the friction losses will decrease to 1/4 if the flow rate is halved.

EXAMPLE: RETURN SLUDGE FLOW RATE DECREASE

One experience is reported from the Rya Wastewater treatment plant, Sweden. Energy could be saved by decreasing the return sludge flow pumping. Of course, the influence of a decreasing return sludge flow rate on the aeration tank performance had to be carefully considered. The average flow rate of the return sludge was decreased from 3.3 to 1.3 m^3/s. This resulted in electrical energy savings of 2.7 *GWh*/*year* or a power saving of around 300 *kW* (Gryaab AB, 2007).

Wastewater pumping causes more wear than clean water pumping. Debris accumulates in sewers and inlet pumps. Fats, oils and greases bind surface debris. Rags, paper and other solids bind round pump shafts and impeller vanes. Valves and other hydraulic fittings are potential blockage points. All of this will result in extra energy requirement and it requires extra care in maintenance of these pumping systems.

The pressure losses depend critically on the pipe diameter that has to be matched carefully to the flow rate. Pipe bendings have to be smooth. Different pipe materials will have significantly different friction.

16.2 LEAKAGES

It is estimated (different numbers from different sources) that 45–88 million m^3 of water is lost every day due to leakages in water supplies. Half of this is in developing countries. The cost is estimated to be over US$ 14 billion. This is enough water to serve some 200–400 million people (Kingdom *et al.* 2006).

45–88 million m^3 of water is lost every day due to leakages in water supplies. This is enough water to serve some 200–400 million people.

Another way to express this fact is that water is energy, and huge amounts of energy are wasted due to leakages. The easiest way to find water is to stop losing it. Water companies are reducing energy use while having to improve and extend their services. In general, water companies have the potential to increase the efficiency of both water and of energy consumption.

Water is lost not only via leakages. There are also apparent (commercial) losses due to meter inaccuracies, data mismanagement, or theft of water through illegal connections. The World Bank estimates that the apparent losses are some 45 million m^3 of water every day (Kingdom *et al.* 2006).

Water utilities around the world lose between 25% and 50% of treated water to leaks. Aging water infrastructures are contributing to the challenges. By the mid-2000s more than half of the 16,000 *km* of water pipes below the streets of London were over a hundred years old and often burst. London had one of the leakiest water systems in the rich world. Every day nearly 900,000 m^3 of treated water were lost and 240 leaks had to be fixed. Still (Evening Standard, UK, 7 February, 2012) three major bursts have happened in London recently, blocking streets and flooding basements. Thames Water representatives stated than 'the significant lack of investment must be addressed'. Over the past five years, though, Thames Water has replaced around 2,000 *km* of cast iron mains with plastic ones, reducing leakage to 670,000 m^3 per day (The Economist, 4 November, 2010). And when the company puts in new pipes, it also installs additional wireless sensors.

Despite water companies largely achieving leakage targets within Europe the energy wasted through leakage is still significant. The American Water Works Research Foundation (AWWARF) states that the inspection and assessment of water pipelines is perhaps the next 'big' issue facing utilities in North America. In Europe, the new European Council Directive 98/83/EC is putting pressure on water companies to improve the condition assessment and continuous monitoring of transmission mains in order to safeguard the security of supply to customers.

The Association of Water and Energy Research Malaysia (AWER) revealed figures on leakages in Malaysia (New Sunday Times, Malaysia, 6 March, 2011). Malaysia lost an estimated RM1.64 billion (≅400 million US$) worth, or 1.8 billion m^3, of treated water in 2009 due to wastage. This corresponds to 36% water wastage. In Malaysia it is estimated that 6000 *km* of pipes are more than 40 years old. They will burst easily and should be replaced. The cost to replace 1 *km* in an urban area could go up to RM500,000 (≅120,000 US$). This means that the yearly loss due to non-revenue water (NRW) corresponds to the replacement of more than 3000 *km* of pipes.

The financial loss caused by NRW – through leakage, theft or metering errors – is significant in many countries. Much of the leakages are caused by too old pipes that will become increasingly sensitive to high pressure and mechanical stress. There is a direct correlation between decreasing NRW and improving water quality. The more breaks there are, the higher the probability for infiltration.

Within IWA there is a Water Loss Task Force addressing the water loss issues (Lambert, 2003). It is claimed that high NRW levels are the single biggest reason for poor utility performance. The IWA task force has identified four methods to tackle the leakage and NRW problem:

- pressure management (see Section 16.3),
- active leakage control,
- pipe materials management, and
- speed and quality of repairs.

16.2.1 Leakage detection and localization

A large number of leakage detection and location techniques have been applied in real systems or have been described in the literature (Misiunas, 2005a). Some of the existing techniques are designed for detecting leakages only and are not capable of locating them while others are developed specifically to locate leaks. Then there are methods that allow for both detection and location. Active leakage control – to find the location of underground leaks – can range from having personnel walking the streets listening for leaks to using automatic systems for continuous leakage detection and localization.

Commercially available leakage inspection methods can generally be divided into two large groups – acoustic and non-acoustic inspection techniques. In addition, transient-based leak inspection methods have been given a lot of attention from the research community. These methods will allow the network to be monitored at all times, and the system will allow immediate reaction if an unusual pressure or flow rate situation would appear.

16.2.2 Single pipes

In a main pipeline of a water transmission line an automatic periodic leakage diagnosis system can be implemented. At the cost of installing a single pressure monitoring point, sudden bursts at any point along the pipeline can be detected and located with an impressive accuracy. The pressure changes have to be measured with high frequency. In this way the transient response of the pressure wave caused by the burst is monitored (Misiunas *et al.* 2005b).

The leakage detection technique can also be applied for detecting other hydraulic faults, such as blockage or entrapped air pockets. The performance of the failure management techniques has been evaluated based on:

- the minimum size of the failure that can be detected and located,
- the precision of the derived location, and
- the detection and location time, that is, the time from the actual failure to the time when it is detected and located.

The burst monitoring technique offers an immediate reaction to potentially hazardous pipe ruptures. Losses associated with pipe failure can be reduced significantly having a monitoring system installed. Water loss is of course important, but property damage and liability are the compelling issues.

16.2.3 Pipe networks

A burst can be detected and located not only in a single pipe, like a transmission system, but also in a water distribution *network* Misiunas *et al.* (2005c, 2006). The technique is based on the real-time continuous monitoring of the network inflow at the entry point of the network, typically a district metered area (DMA). The pressure is measured at a number of points within the network. Thus, the burst can be detected and located directly after it occurs and the isolation time can be minimized preventing the large losses associated with a pipe failure. This approach is designed for medium to large bursts with opening times in the order of a few minutes and is suitable for networks of relatively small size, such as a DMA. The flows and pressures in the network are simulated off line using a distribution system model. A sensitivity-based sampling design procedure is introduced to find the optimal positions for pressure monitoring points. Typically there may be 3–4 pressure measurement points in a system with a hundred nodes.

The burst-induced increase in the inlet flow rate is detected using a change detection test in real time. Various bursts have been simulated off line so as to obtain a small database of possible burst locations and corresponding pressures. Based on parameters obtained in the change detection test, the burst is simulated at a number of burst candidate locations. The changes in pressure at the pressure monitoring points obtained from the off-line simulations are then compared to the measured values and the location resulting in the best fit is selected as the burst location. The proposed burst detection and location technique has been demonstrated to be extremely promising.

A monitoring system can analyse grid data continuously. This can be correlated to other information. For example, every unexpected spike in the water flow is not the result of a leakage. It can be the result of coordinated actions from the customers, for instance the water (and energy) use at half-time during World Cup football matches. Online data have to be compared with historical data to provide a basis for comparison, enabling the algorithms to detect things that are about to go wrong.

Leakage control has come a long way in the energy industry, for example for oil pipelines (compare Chapter 11.3). Surely, the water and energy industries can learn a lot from each other by coming together to tackle many problems related to liquid losses.

Researchers in the Centre for Water Systems at the University of Exeter, UK have pioneered new methods for detecting pipe leaks and urban flooding, using artificial neural network theory. Most available models are based on solving a set of partial differential equations that require a huge computational effort. Researchers are increasingly interested in an alternative grid-based approach called Cellular Automata due to its computational efficiency (Guidolin *et al.* 2011).

16.3 PRESSURE CONTROL IN WATER DISTRIBUTION

A water distribution pipe is supposed to have a sufficient pressure in order to keep up the flow, even at the farthest tap and at peak hours. A conventional solution keeps the pressure at the pumps in the waterworks at a given level, so that all customers will obtain sufficient pressure. As water is consumed along the distribution pipe the pressure will decrease along the pipe. Therefore the pressure at the waterworks has to be kept sufficiently high so that the most distant consumer (the *critical point*) will have sufficient pressure all the time. During the night only little water is used, and consequently the pressure losses are smaller and the pressure is mostly kept higher than necessary along the distribution pipe. As a result, there are wide swings in the pressure at the distant part of the network.

In the conventional – constant pressure – control the pressure is kept high *at the water works*. The flow rate is then controlled via pressure reducing valves in the distribution pipe. As we have seen in 16.1 this causes an energy loss. Keeping the pressure high all the time at the point of delivery will wear out the equipment and also consume too much electrical power. As a result there is a higher mechanical stress than necessary onto the pipes and the risk for cracks in the pipes will get larger. This will increase the probability for bursts and leakages. Naturally this becomes more serious as the pipes get older. Also, if there is a crack, the leakage will become bigger if the pressure is higher. Furthermore, if there is a leakage in the system more energy is required to maintain the pressure. More water will be pumped, which will cause even more water leaking out.

16.3.1 Variable pressure control

The new thinking is to keep the pressure constant *at the consumer*. The pressure in the network should be maintained as low as possible, but still satisfy even the most distant customer (the critical point) at all times. Then the pressure in the pipes can be reduced, thus decreasing the mechanical stress and at the same time saving electrical power. With a lower pressure the flow will decrease, but still be adequate, and any leakage will be less serious due to the lower pressure. A solution of this kind will require a more flexible pumping system. Pump units have to be placed at various points in the network. In this way there are actuators that can maintain the pressure at various points in the network.

The desired pressure at the most distant customer has to guide the pressure in the water distribution system. It should be allowed to be variable.

To control the pressure in the critical point the signal from a pressure sensor has to be transferred via a wireless connection to a server. A digital controller in the server calculates the necessary pressure at the head end of the pipe and the pressure reducing valve will be remotely controlled to supply the necessary pressure in the distribution pipe. The pressure towards the head end of the pipe is now controlled so that the pressure at the critical point is kept at its minimum.

This solution solves only part of the problem. The pressure at the water works is still kept constant and there is an energy loss over the pressure reduction valve. The next improvement is obtained if the pump at the waterworks is a variable speed pump that can maintain a variable pressure so that the pressure reduction valve can be fully open all the time. It is even better if the pressure reduction valve is replaced by a variable speed pump.

Today variable pressure in water distribution systems is a proven technology, but still most systems are based on the old thinking. Then we are reminded that 'nothing is new under the sun'. The idea of controlling the supply pressure in water distribution systems was presented already in 1985. The system was in operation in Takamatsu City, Japan (Shimauchi *et al.* 1985). The progress in network calculations had recently been possible by the computer development. Two other applications of variable pressure control were implemented in the UK in 1985 (Olner, 1985; Parker, 1985). The telemetry systems made it possible to remotely control the valve settings in water distribution zones. Today the telemetry systems are replaced by mobile telephone networks for the communication between the pressure sensors and the remotely controlled valves. Variable speed pumping is a proven technology today and can provide further energy reduction.

The IWA Water Loss Task Force studied NRW in 112 systems in 10 countries. It was found that a 10% average decrease of the maximum pressure resulted in a 14% reduction in burst frequency in mains and service pipes. On top of that there are significant energy savings. Results from the Gold Coast, Queensland, Australia are encouraging: after pressure management had been implemented the reduction of service breaks were reduced by 73% and main breaks by 56% (Lambert-Waldron, 2010).

Maintaining a variable pressure in a water distribution system will save energy and also reduce the leakage in the downstream distribution network.

16.4 CHAPTER SUMMARY

Pumping is a critical operation in all water and wastewater operations. There are obvious incentives to minimize pumping energy. This can be done by variable speed systems and by ensuring that the efficiency is the best at the most common flow rates.

The design of the piping system has a lot of influence on the energy demand, not only the diameter and the pipe material, but also corners, valves and other blockages.

Leakages are too common in water distribution systems. Today there are proven methods for automatic leakage detection and localization. This can save not only significant volumes of water but also damages caused by the leaking water.

Pressure control in water distribution networks should be variable and kept at a minimum. It has to be controlled so that the most distant customer is satisfied at all times. This will not only save energy, but will also reduce the risk for leakages.

16.5 MORE TO READ

Many pump manufacturers provide information about pumping principles and equipment. Grundfos Pump Handbook presents an excellent description of pumping principles (www.grundfos.com).

Some results of LCA for pumping rainwater is considered in Ward *et al.* (2010). Fowler-Main (2010) describe pump scheduling for water distribution. Van Schagen *et al.* (2010) have analysed short term prediction for water distribution to decrease pumping costs. Solar array based pumping technology is now commercially available. One example is the Lifelink concept from Grundfos.

IWA (International Water Association) has a Task Group on Non-Revenue Water Management for Intermittent Supplies, described on the IWA web page (www.iwahq.org). Fitzpatrick (2010) presents an overview of water loss problems.

Thornton-Lambert (2006) and Fitzpatrick (2010) present a good description for the non-expert of pressure control. Successful implementations of variable pressure control in water distribution systems are reported by i2O (www.i2owater.com) and Grundfos (www.grundfos.com).

17

Aeration in biological wastewater treatment

> *Aerate: to supply with oxygen. The blood is aerated in the alveoli of the lungs.*
> The American Heritage Dictionary.

The most common process for removing organic matter is biological oxidation, which involves microorganisms feeding on the carbon and the oxygen in the water. Around half of the organic matter is used for the growth of the microorganisms, in other words to increase the body mass. Half of the organic matter is converted into carbon dioxide. To aerate the biological reactors is an energy consuming process. This means that the aerator has to be controlled so that it balances between the biological need for oxygen and the energy cost to supply the air.

Nitrogen principally arrives at the plant as ammonium NH_4^+ (60–80%). Most nitrogen removal plants will transform the ammonium into free nitrogen that will escape via the water surface. The removal of nitrogen is a slower process than the removal of organic carbon and takes place in two principal stages, nitrification and denitrification. In the first process ammonium is transformed into nitrate NO_3^- (an oxidation process) and in the second process the nitrate is reduced to nitrogen gas N_2 (compare Chapter 15.4).

The concentration of dissolved oxygen (DO) governs carbon removal, nitrification as well as denitrification. In the carbon removal and nitrification the process rate will increase with the oxygen concentration. However, there is a limit to the process rate, and higher DO concentrations will not help the biology but only waste energy for the compressors that aerate the biological reactor. With too little DO the microorganisms (like humans) will suffocate and the process rate will be significantly reduced, as illustrated in Figure 17.1. In the extreme case the organisms will die. The opposite applies to the denitrification: the higher level of dissolved oxygen the lower the rate.

Aeration typically represents 50% to 60% of a sewage treatment works energy demand (Brandt *et al.* 2011) but energy consumption as high as 75% has been reported (Rosso *et al.* 2008). Therefore any improvement in aerator performance will have a significant impact on the overall energy demand for the treatment works. This fact explains why aeration control is a key operation.

The air supply process is briefly described in 17.1 and it is demonstrated that the spatial distribution of oxygen in the reactor has to be satisfied. Then the concentration has to be satisfactory at all times, and this is further explained in 17.2. Dissolved oxygen control is a key operation in all biological wastewater treatment.

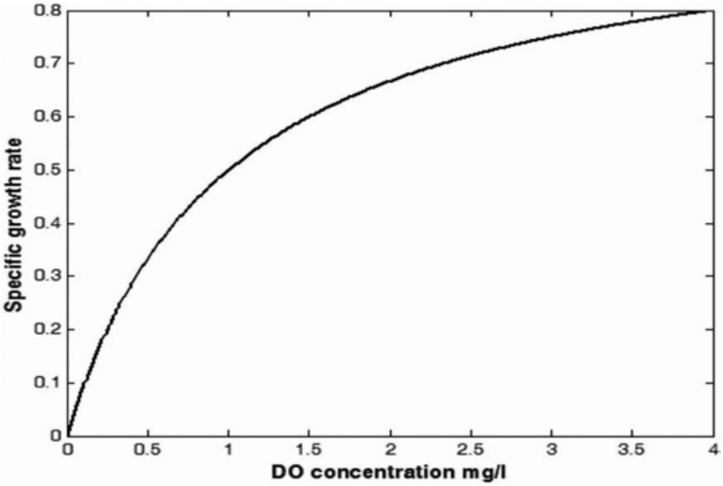


Figure 17.1 The aerobic microorganism growth rate as function of the dissolved oxygen concentration.

17.1 AIR SUPPLY

An adequate design of the aeration system is the pre-requisite for an energy efficient aeration. There are two principally important parts, the compressor and the diffuser system. The compressor has to allow for variable air flow rates, which is crucial for any control of the dissolved oxygen. A diffuser system that forms fine bubbles in the water is more energy efficient than a coarse bubble system. There is a basic physical reason for this. The rate of the mass transfer of gaseous oxygen to DO depends on the relation between the surface area and the volume of the air bubbles, that is as 1/r, where r is the bubble diameter. So, if the diameter of a bubble is halved then the ratio of surface to volume will double. The contact time between the air bubbles and the water is also important. Small bubbles rise more slowly than large bubbles and have longer contact time.

Many activated sludge reactors are designed as a long tank or as a series of tanks. As the wastewater enters the biological reactor the organic matter concentration (expressed in COD in Figure 17.2) is relatively high. The microorganisms will be active and growing and the oxygen demand is high. As the water flows towards the outlet of the tanks the organic matter is consumed and the resulting oxygen consumption is low. It is still common that there is a uniform air supply along the tank. Since the oxygen demand is high in the inlet area and low towards the outlet the DO concentration is low at the inlet and quite high at the outlet, as illustrated in Figure 17.2.

Normally the microorganisms require around 1–3 mg/l of DO. As Figure 17.2 illustrates a lot of excess oxygen is supplied towards the outlet of the tank. This results in energy waste. The situation is similar for nitrification systems. The organic matter is consumed mainly by heterotrophic organisms, while the ammonium nitrogen is oxidized to nitrate via autotrophic organisms. The DO requirement is larger for the autotrophic than for heterotrophic organisms. The autotrophic organisms are slower than the heterotrophic ones, which means that ammonium is removed slower than the organic matter. This is illustrated in Figure 17.3. Just before the middle of the reactor the DO concentration rises quickly. This is an indicator that the organic matter has been consumed. The ammonium still is getting oxidized and continues to consume oxygen along the reactor. At the outlet all ammonium has been oxidized into nitrate.

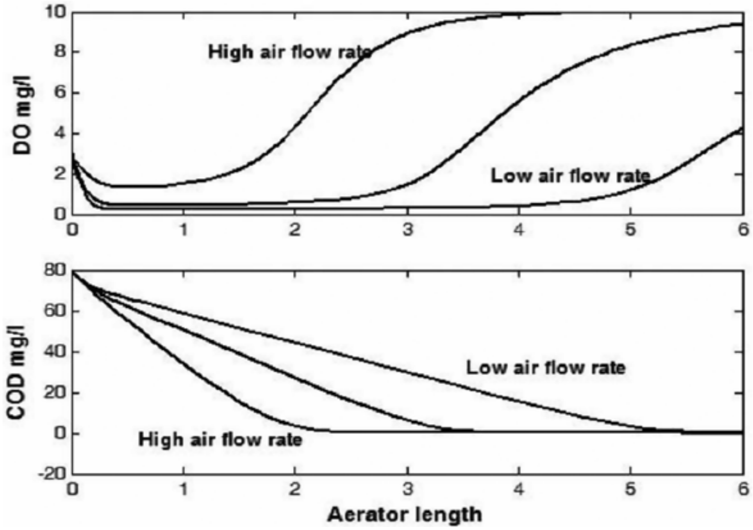


Figure 17.2 The DO profile in a plug-flow reactor for carbon removal with uniform airflow distribution. The upper figure shows the DO profile (mg/l) for different air flows. The lower figure depicts the corresponding carbon concentration (mgCOD/l) decrease along the plug flow reactor.

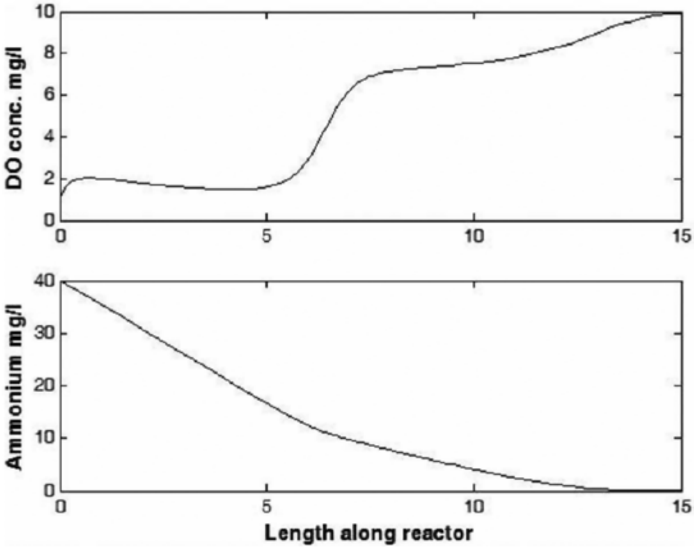


Figure 17.3 The DO profile in a plug-flow reactor for carbon removal combined with nitrification. The airflow distribution is uniform. The upper figure shows the DO profile (mg/l) and lower figure depicts the corresponding ammonium concentration decrease along the plug flow reactor.

Dissolved oxygen concentration has to be sufficiently high to satisfy the microorganisms, but limited to save energy.

17.2 DISSOLVED OXYGEN CONTROL

The DO concentration is varying not only along the reactor but also as function of time. The reason is that the organic and nitrogen load to the plant varies significantly and quickly. It is obvious that we would like to have a DO concentration that is constant both in space and in time. In order to achieve this we need:

- supply a variable air flow from the compressor;
- control the air flow distribution along the reactor, that is, having air flow valves along the reactor that can be controlled individually;
- measure the DO concentration at suitable locations;
- implement adequate control algorithms.

All wastewater treatment plants are subject to disturbances, in flow rate, concentration and composition. Often there can be a factor of ten between the lowest and highest load. Naturally this will influence the oxygen demand of the microorganisms. A control system has to be able to manipulate the air supply to the reactor to compensate for the disturbances. This has the double purpose of supplying adequate oxygen for the microorganisms while saving as much energy as possible.

The control of aeration has been the subject to considerable research since the 1970s, when the dissolved oxygen (DO) sensors reached a level of robustness and precision suitable for feedback control. Today, the control of DO to a set-point is considered a mature technology from a methodological point of view. However, it should be remembered that the actuators (compressor, piping, valves) are crucial. The compressor has to allow a variable air flow that is required by the control system. Still there may be inadequate capacity of the blowers for very high loads.

It is not apparent how to select the best value of the desired DO concentration. This depends on many factors and is different for different microorganisms. However, the level of desired oxygen can be estimated from ammonium measurements. Figure 17.3 illustrates how the ammonium approaches zero concentration towards the outlet. If the outlet concentration is higher, then there may be insufficient aeration, and more air can be commanded. Conversely, if the ammonium concentration approaches zero too early in the reactor, then the control has been too ‘ambitious’ and the air supply can be lowered. DO control based on ammonium measurements is a proven technology today (Åmand *et al.* 2013).

The energy savings by DO control can be significant. The first phase, controlling the DO to a constant value despite the load changes, can save 30–50% and even more in some cases. The second phase, to base the desired DO concentration on ammonium measurements, can save another 10–15%. Then a third phase can save further energy, to allow the air pressure to be variable, depending on the load (Olsson *et al.* 2005).

DO control saves energy and compensates for load disturbances.

17.3 CHAPTER SUMMARY

Aeration is a critical operation in most wastewater treatment. It is a major energy consumer together with pumping. Therefore aeration control is important. Aeration control aims not only at energy savings but will guarantee that the microorganisms are adequately supplied with oxygen at all times. A variable setpoint (desired DO concentration) is made possible by ammonium measurements. Further energy reduction can be obtained by allowing variable air pressure in the system.

17.4 MORE TO READ

There are literally hundreds of publications on DO control and aeration. The textbook Olsson-Newell (1999) and the state-of-the-art report Olsson *et al.* (2005) describe DO control in detail. In Olsson (2012) a personal review and history of DO control is found. Åmand *et al.* (2013) gives a comprehensive review of dissolved oxygen control. Svardal-Kroiss (2011) discuss aeration energy requirement. Brandt *et al.* (2011) give a lot of practical insight how to improve the performance of aeration systems.

18 Biogas generation and use

> *Eat more beans – America needs the gas.*
> Bumper sticker during the oil crisis in the 1970s.

Organic material can break down to biogas by anaerobic digestion (fermentation). Methane and power produced in anaerobic digestion facilities can be utilized to replace energy derived from fossil fuels, and hence reduce emissions of greenhouse gases. In most agriculture today manure is disposed of in lagoons or stored to decompose. As a result of this two greenhouse gases are released, methane (CH_4) and nitrous oxide (N_2O), which have a large global warming potential (see Chapters 4.7 and 15.4). Converting this manure to biogas will not only provide a lot of renewable energy; it will also limit the greenhouse gas emissions. Manure from just one cow can produce as much as 3–6 kWh in a day.

We discuss the energy content of wastewater and of organic waste in 18.1. The interesting energy product biogas and its composition is described in 18.2. Anaerobic digestion is the key process to obtain biogas and the basics is described in 18.3 and the operation in 18.4. Biogas is getting increasing attention as an energy source, as demonstrated in 18.5.

18.1 ENERGY CONTENT

The organic matter content (COD) of wastewater can be considered an energy source. Nearly all wastewater has an energy value of 13–15 kJ/g COD. A detailed analysis of municipal treatment plants in Austria showed that 110 g/person of COD is generated every day and the energy content is significant, as shown in Table 18.1. It gives an indication that a lot of energy can be utilized. The COD content in municipal wastewater (Europe) represents a chemical energy of about 18 W/person (heat of combustion energy). In theory, this energy can be recovered. It is sufficient to design the self-sufficient wastewater treatment plant. The total energy input to the whole water cycle is not more than 10 W/person, so the organic load is a most important source of energy.

Table 18.1 Energy content of municipal wastewater COD.

COD energy		
Energy value	13–15	kJ/kg COD
	3.5–4	kWh/kg COD
Production	110	g/person/day
	40	kg/person/year
Energy value	~150	kWh/person/year

Source: Svardal-Kroiss (2011).

> *The organic matter content in wastewater is usually sufficient to make the wastewater treatment plant energy neutral or even energy positive.*

Biogas is considered more efficient regarding energy per agricultural land (hectars) than bio-ethanol and bio-diesel. This will be further discussed in Chapter 22. In this chapter we will discuss the anaerobic digestion from two water-energy aspects:

- Applying anaerobic digestion as a more energy efficient operation than aerobic treatment for wastewater treatment. The main purpose of this operation is wastewater treatment and environmental protection. The feedstock contains mainly wastewater from industries, agriculture or municipalities.
- Using anaerobic digestion with the specific purpose to produce biogas, that is to produce bio-energy. The feedstock is obtained from manure, food and kitchen wastes, sewage sludge and energy crops.

In European countries these two applications are named differently: 'anaerobic wastewater treatment' and 'biogas plant operation' respectively. However, in China all operations producing biogas are called 'biogas plant operations'.

There is a significant difference between the energy requirements for aerobic and for anaerobic treatment of organic waste. Let us consider the requirements for degrading organic waste, measured as 100 kg COD. The results are compared in Table 18.2. From the table we derive that the calorific value of methane gas is 285/35 ≈ 8 kWh/m^3. Common values, found in literature, of energy content from municipal solid waste are 8–10 kWh/m^3. About 32% of the energy can be transformed into electricity by means of combined heat-power units (CHP) or into mechanical power, which means around 3 kWh of electrical energy per Nm^3 of methane gas. Notice in Table 18.2 that the aeration energy is in terms of electrical energy, while the biogas energy content is chemical energy contained in the biogas.

Table 18.2 Comparison of aerobic and anaerobic degradation of COD.

	Input	Output
Aerobic	Influent: 100 kg COD	Heat loss
	Aeration energy ≈100 kWh	Sludge 30–60 kg
		Effluent 2–10 kg COD
Anaerobic	Influent: 100 kg COD	Biogas ≈ 35 m^3 (≈285 kWh)
		Stabilized sludge 5 kg
		Effluent 10–20 kg COD

Source: Steyer (2005), Chapter 7 in Olsson *et al.* (2005).

In developing countries, simple home and farm-based anaerobic digestion systems offer the potential for cheap, low-cost energy for cooking and lighting. The organic material that provides the feedstock to the anaerobic digestion may consist of wastewater, manure from pigs and cows, municipal solid waste, food residues and agricultural residues.

In Chapter 15.6 we discussed wastewater treatment as a 'resource recovery plant'. The production of biogas from anaerobic treatment is a key component in such a plant. The biogas can be converted into energy to power the operation of a wastewater treatment plant (WWTP).

Alternatively the biogas can be used to deliver heating energy externally or upgraded to vehicle fuel. Many positive experiences have been reported of using biogas to make the wastewater operation more energy efficient. One example is the full scale experiments at the Prague's Central Wastewater Treatment Plant (Jenicek *et al.* 2013). The biogas operation was optimized to increase the specific energy production from approximately 15 to 23.5 kWh per population equivalent per year. The results suggest that even wastewater treatment plants with 'conventional' energy consumption can be close to energy self-sufficient.

18.2 BIOGAS COMPOSITION

Biogas as the end product can be utilized for heating, for electrical energy production or for vehicle fuel. Biogas consists primarily of methane (CH_4) and carbon dioxide (CO_2) and may have small amounts of other components as shown in Table 18.3, as well as moisture.

Table 18.3 Main components of raw biogas.

Component	%
Methane CH_4	50–75
Carbon dioxide CO_2	25–50
Ammonia nitrogen NH_3	0–10
Hydrogen H_2	0–1
Hydrogen sulfide H_2S	0–3

Source: DOE (2013b).

The composition of biogas depends on the feedstock that supplies the anaerobic digestion process. Advanced waste treatment technologies can produce biogas with 55–75% CH_4.

The flammable component of biogas is methane. Therefore the amount of methane contained in the biogas should be as high as possible. Biogas can be cleaned and upgraded to natural gas standards when it becomes biomethane and be used as vehicle fuel (Lindeboom *et al.* 2011; Ryckebosch *et al.* 2011). This means that the methane content is >97% and the carbon dioxide is <3%.

When methane is burned, 1 m^3 of the gas yields about 10.4 kWh. This is the same energy content as 1.1 liters of gasoline, or 1.3 kg of charcoal (see Appendix A2). When 1 m^3 of biogas is burned the energy yield is about 0.104 kWh per percent of methane. For example biogas composed of 65% methane yields around 6.8 kWh/m^3.

Methane is the key energy component of biogas.

Around 3–6% of the total energy output in gas is required to perform the upgrading of the biogas. The cost for upgrading is considered to be 15–20% of all the costs, while the digestion is 80–85%.

Biogas can be used for direct heating of the digester and for space heating. Else it can be used for electric energy production in a wastewater treatment plant by using a CHP gas engine. The waste heat from the engine can then be used for heating. Finally the (upgraded) biogas may also be used for vehicle fuel or be delivered to a gas grid. A lot of biogas is also used for district heating, for example in several cities in Sweden.

18.3 ANAEROBIC DIGESTION

Anaerobic bacteria are some of the oldest forms of life on earth. The same types of anaerobic bacteria that produce natural gas in nature also produce methane in the technical processes. Anaerobic bacteria evolved before the photosynthesis of green plants released large quantities of oxygen into the atmosphere. Anaerobic bacteria break down or 'digest' organic material in the absence of oxygen and produce biogas as a waste product. Anaerobic decomposition occurs naturally in swamps, water-logged soils and rice fields, deep bodies of water, and in the digestive systems of termites and large animals.

In the anaerobic process microorganisms assist the process of organic material conversion that produces the biogas. The processes involved in fermentation are exceedingly complex, and are not completely understood. There is an impressive activity going on in anaerobic process research to increase the knowledge of the microbiology and the internal mechanisms taking place.

Biogas fermentation can be classified into two or three classes:

- Wet fermentation, where the total solids (TS) content is <10%;
- Semi-dry fermentation, where the TS is around 10–20%, and
- Dry fermentation, where the TS >20%.

In a wastewater treatment plant there is usually wet fermentation. The low content of TS naturally makes the biogas yield smaller. The dry fermentation is attractive from a biogas production point of view, since an increasing concentration of dry matter is obtained.

Four principal steps take place in the anaerobic process:

- *Bacterial hydrolysis*: the input material contains insoluble organic polymers that are broken down by the microorganisms in order to make them available for other bacteria as sugars, fatty acids and amino acids.
- *Acidogenesis*: Acidogenic (fermentative) bacteria convert the sugars, fatty acids and amino acids into carbon dioxide, hydrogen, ammonia, organic acids (VFA, volatile fatty acids) such as acetic acid (CH_3COOH) and propionic acid (CH_3CH_2COOH), and alcohols (for example ethanol CH_3CH_2OH).
- *Acetogenesis*: the resulting organic acids are converted by acetic acid-forming bacteria (Acetogens) into acetic acid as well as additional ammonia, hydrogen and carbon dioxide.
- *Methanogenesis*: methane-forming archaea (Methanogens) convert these products to methane (CH_4) and carbon dioxide (CO_2). Methanogenesis is sensitive to the pH, which requires good monitoring and control.

The remaining, non-digestible material that the microbes cannot feed upon makes up the digestate. Digester liquor can be used as a fertilizer, while the solid component of the digested material can be used as a soil conditioner to increase the organic content of soils. The liquor can replace chemical fertilizers that require large amounts of energy to produce and transport. Therefore the anaerobic digester liquor can be used to decrease the carbon footprint in agriculture.

A variety of factors affects the rate of digestion and biogas production. The most important is temperature. Anaerobic bacteria communities can endure temperatures from below freezing to more than 60°C. Different species of bacteria thrive in different temperature ranges. At temperatures in the range 35–40°C there are mesophilic bacteria. Some of the bacteria, Thermophiles, can survive at temperatures around 50–65°C. The Mesophiles are generally more tolerant than Thermophiles to changes in environmental conditions. Therefore mesophilic systems are considered to be more stable than thermophilic digestion systems. However, at increased temperatures the reaction rates are faster and consequently the gas yield is faster. The hydraulic retention time and smaller reactor volumes are required under thermophilic conditions. At lower temperatures the bacteria activity, and thus biogas production, falls off gradually from 35°C to 0°C.

Rapid changes of the reactor temperature will upset the bacterial activity. Therefore the digester must be kept at a consistent temperature. In many countries in temperature zones, such as Europe and North America, digestion vessels require some level of insulation and/or heating. In some installations part of the biogas is burned to heat the digester.

There are several advantages of anaerobic digestion (AD). We have primarily emphasized the energy aspects but there are other positive aspects, such as:

- AD has a high capacity to treat slowly degradable substrates at high concentrations;
- The sludge production is very low, some 5–10 times lower than in aerobic processes (Table 18.2);
- AD can efficiently reduce pathogens.

However, there is always a price. Among the technical barriers for AD we find:

- The low sludge production is closely linked to the slow growth of microorganisms;
- The start-up of an AD process is tedious;
- AD microorganisms are highly sensitive to overloads of the process. For example, methanogenic biomass is inhibited by high concentrations of its own substrate (such as volatile fatty acids);
- The AD is a complex process. Hundreds of species of organisms are involved in the AD reaction scheme. Many of these reactions are still not completely known;
- The lack of knowledge often leads to breakdowns, mainly due to organic overload. This often creates a suspicion towards this process.

18.4 ANAEROBIC DIGESTER OPERATION

Acidogenic bacteria produce acids such as VFA and consequently will reduce the pH of the reactor. This is of importance for the methanogenic bacteria, since they have to operate in strictly defined pH and temperature ranges. Therefore, the biological reactions of the different species in a reactor can be in direct competition with each other. The anaerobic digestion is often realized in two stages. Typically hydrolysis, acetogenesis, and acidogenesis occur within the first reaction vessel. Acidogenic bacteria will grow more quickly than methanogenic bacteria. The organic material is then pumped into the second stage, the methanogenic reactor. In two-stage mesophilic digestion, residence time is of the order 15–40 days.

In any typical AD operation there is a variable composition and flow rate of the influent feed. It is crucial to know the substrate composition of the feedstock to determine the methane yield and methane production rate from the digestion. Even if the anaerobic process can accept any biodegradable material the gas yield depends critically of how digestible the material is. Therefore, many digesters operate with co-digestion of two or more types of feedstock. Apparently knowing the methane potential is a key information to operate the AD process. Today there are automatic devices that can determine the true biochemical methane potential and dynamic degradation profile of any biomass substrate (www.bioprocesscontrol.com). This allows the operator to readily determine the optimal retention time and mix of substrates for co-digesting.

Another aspect of automatic determining the biogas potential is commercial. An operator receiving organic material for biogas production can select and price substrates according to their true energy content of biomass. This will help the biogas operators and substrate suppliers to better control their substrate economy, having a positive impact to overall profitability.

Often there is no information available from the reactor, and only the biogas output flow is measured. This means that the operator knows very little about the progress of the operation, and the information of the gas flow comes much too late. Consequently the AD processes are often operated far below the max capacity. It is obvious that more instrumentation and advanced control can address several of these problems. Better control can also achieve a good rejection of disturbances. Various control strategies have been proposed, notably by Steyer *et al.* (1999), Liu *et al.* (2004), Alcaraz-Gonzáles *et al.* (2005), Bernard *et al.* (2005), and Lardon *et al.* (2005). J.P Steyer has written an excellent overview of control of AD processes in Chapter 7 of Olsson *et al.* (2005) and in Steyer *et al.* (2006). In our research (Liu *et al.* 2006) we found that the controller itself and the control structure can be quite unsophisticated in the sense that a variable gain low order controller can achieve great improvement of the operation. The system efficiency is maintained while process stability is ensured.

A major goal for the AD operation is to keep the process stable and efficient. The stability can be quantified with the biogas production rate and the gas composition as well as the level of VFAs in the reactor. One goal is to keep the pH within the allowed window so that the methanogenic bacteria can survive and produce gas. Another goal is to maximize the throughput in order to maximize the biogas production. This requires four strategies:

- Design a suitable reactor configuration. Mostly a multi-stage design will allow a separate optimization of the processes in different stages;
- Mix and pre-treat the feedstock properly in order to get the best biogas production potential;
- Study the microbiology to gain process knowledge;
- Supply the process with adequate instrumentation and control.

An advanced plant operation should be able to measure:

- *In the gas phase*: the biogas flow rate and composition;
- *In the liquid phase in the reactor*: levels, flow rates, temperatures, pH, alkalinity, as well as VFA and dissolved hydrogen (H_2) concentrations;
- *In the feed*: the total solids, the volatile solids, the COD, the BOD and the moisture.

All these factors can be summarized in the biochemical methane potential (BMP), see Angelidaki *et al.* (2009). Still there is a lack of reliable sensors, but a lot of development is taking place. Depending on the reactor configuration there are various variables to manipulate. The most important ones are:

- Pump speed of loading rate for the feedstock;

- Recycle flows;
- Chemical or additives dosing volumes, such as H_2S removal and nutrient addition.

The highly dynamic character of the AD process becomes apparent as the process is operated close to its maximum capacity. To bring the process towards maximum biogas production while ensuring stable operation at a high organic loading rate will require more advanced control. In recent years there has been a lot of research and development on monitoring and control of the AD process.

18.5 BIOGAS DISTRIBUTION AND USE

The biogas produced in a wastewater treatment plant can be used primarily to heat the digester to the required temperatures. Sometimes it is used to run a gas engine to produce electrical power that can be used for example to run the compressors for air supply. Note however, that when the energy in the biogas is converted to electrical power there is only about 35–40% efficiency. Some waste heat from the engine can be utilized to heat the digester.

The upgraded biogas can be used for vehicle fuel. If a local gas network allows, the biogas can be injected in the pipeline.

The scope for biogas generation from non-sewage waste biological matter – energy crops, food waste, abattoir waste, and so on – is much higher. Biogas plants for agricultural waste, such as animal waste and energy crops are expected to contribute to reducing CO_2 emissions and provide the farmers with renewable fuel as well as with additional revenues. In rural areas the production and consumption of biogas are close to each other. In a large nation like China there is a huge interest in biogas, and 185 million people are said to be depending on the biogas. There is a great demand to replace coal burning with biogas.

Biogas will play a major role in renewable energy (RE) supply also in a nation like Germany, at least until 2030. Germany has relatively little hydropower and a major part of the RE supply until 2030 will be provided by wind energy, on-shore and off-shore. The biogas will make the necessary energy supply expansion possible. After 2030 it is expected that photovoltaic energy will be increasingly important (personal communication, Bernhard Raninger, GIZ, Deutsche Gesellschaft für Internationale Zusammenarbeit, www.giz.de).

Biogas can play a great role in the energy supply, and there are some development lines that should be observed:

- By applying advanced biogas technology in combination with monitoring and control the biogas production can be maximized and the process operated stable and efficient.
- *Pre-treatment* and the proper *composition* of the feedstock are essential for high productivity. Thermal hydrolysis was first applied to improve sludge dewaterability. It could break down the structure of the sludge by breaking the cellular walls of the bacteria and thereby releasing the strongly biodegradable cellular liquid. This would in turn enhance the anaerobic digestion.
- The possibilities of *co-digestion* have to be explored. By providing the right mix of organic materials the bio-methane potential can be maximized.

> The energy crops should be used for biogas rather than for liquid fuels like bio-diesel and bio-ethanol.

From a business point of view there should be a huge potential to better use available capacity in anaerobic digesters, to make biogas production profitable by co-digestion and upgrading the product. Obstacles in terms of regulations and tax rules have to be reconsidered from an environmental point of view, where carbon footprints and environmental friendly energy is valued properly.

Transport fuel is one of the most difficult areas to find a replacement for in the global energy mix. Using biogas for vehicle fuel will have a climate improving consequence. On top of the climate benefits and increased use of vehicle gas yields other advantages. Gas-powered vehicles reduce emissions of nitrous oxides, sulphur oxides and particulates.

Despite the fact that renewable energy in general and bioenergy in particular is subject of head wind biogas is making progress. In 2013 Europe had over 14,500 biogas plants and more than 7,850 MW_{el} of installed capacity. The development of biogas upgrading to biomethane is led by Germany followed by Sweden (European Biogas Association, 2014, http://european-biogas.eu). On a global scale biogas is increasingly being converted to natural gas for injection into pipelines or use in vehicles. IEA Bioenergy Task Group 37 gives a summary of the biogas production and use in 13 countries (IEA Bioenergy, 2014). Germany is the biggest producer among these countries with more than 9000 biogas plants. No other member country today has more than 1000 biogas plants. Around 0.5–2 TWh of biogas is produced annually in most countries except for UK and Germany. UK produced 10 TWh, mostly electricity, during 2012, while Germany generated 40 TWh as electricity.

The biogas produced is mainly used for generation of heat and electricity in most countries with exceptions for Sweden and Switzerland where approximately half of the produced biogas is used as vehicle fuel. Many countries, such as Denmark, Germany and South Korea, among others, show initiatives and interest in increasing the share of the biogas to be used as a vehicle fuel in the near future. In Sweden the biogas production was around 1.7 TWh during 2013. Most of it, 54%, was upgraded to vehicle fuel and 31% was used for heat production. Only 3% was converted to electrical power, while 11% was flared.

The biogas opportunities in the US are vastly underutilized, according to World Bioenergy Association, WBA (www.worldbioenergy.org). There are about 2,200 sites producing biogas in the country, much less than Europe's 14,500 plants. WBA provides bioenergy statistics for many countries in the world.

18.6 CHAPTER SUMMARY

Biogas production is becoming increasingly interesting and important. By extracting the energy of the organic matter in wastewater or in other forms of biomass biogas becomes an important energy source. Furthermore, anaerobic digestion is an attractive waste treatment operation:

- It is favourable from an energy point of view;
- It has a high capacity to treat substrates at high concentrations;
- The sludge production is very low;
- It can efficiently reduce pathogens.

The AD process is slow compared to aerobic processes and the operational challenges are greater. However, instrumentation, monitoring and control can provide substantial capacity increase while keeping the operations stable.

18.7 MORE TO READ

The basic mechanisms of AD are described by de Lemos Chernicharo (2007). Grady *et al*. (2011) provide a comprehensive basis for the understanding of biological wastewater treatment, including anaerobic digestion. Deublein-Steinhauser (2008) is a comprehensive textbook on biogas, while Gerardi (2003) provides a detailed description of the microbiology of AD. Weiland (2010) gives an overview of biogas production.

19 Heat recovery in the water cycle

> *There is no such thing as reversible processes in nature.*
> Sadi Carnot, initiating the science of thermodynamics, 1824.

Water has the second highest specific heat capacity of all known substances, after ammonia. The reason is the extensive hydrogen bonding between its molecules. This property allows water to moderate Earth's climate by buffering large fluctuations in temperature. It also makes water an excellent heat energy carrier in the urban environment.

Wastewater from industrial processes, from sewage treatment and irrigation outflow is a valuable source of energy, organic matter, nutrients and minerals. During the treatment process many valuable compounds are concentrated in the sludge. In Chapter 18 we have discussed how the organic matter can be extracted as energy. The thermal energy (heat and cold) can obviously be used to recover energy in the water cycle but also to replace other energy sources. This will reduce the carbon footprint.

Until now the thinking of energy neutral or even energy producing buildings almost neglected the role of water and water services. The energy effects by transport of wastewater are overlooked to a large extent. A substantial part of the energy losses are caused by the water services mainly because the cold incoming drinking water is heated (for use as hot water but also because the in-door temperature is higher) and discharged as a higher temperature wastewater.

In order to make the water operations close to energy neutral it is important to consider the whole water cycle, all the way from the water extraction to the final wastewater treatment. This includes the drinking water extraction from surface water and groundwater, the water treatment and distribution, the water use at the customer, the wastewater collection and treatment and the management and control of the effluent water, back to the water sources.

> *The heat content in water supplies and in wastewater is a huge source of energy.*

The overall thermal energy cycles are summarized in Table 19.1.

Table 19.1 Thermal energy in the urban environment.

Heat and cold sources	Means	Targets using the thermal energy
Groundwater	Heat exchangers	District heating
Surface water	Heat pumps	Cooling energy in buildings
Wastewater		Heating energy in buildings
Industrial water systems		

Sources: Sanner *et al.* (2003); Van der Hoek (2011, 2012).

19.1 GROUNDWATER

The thermal energy in groundwater or aquifers offers interesting energy savings opportunities. In wintertime in a temperate zone groundwater can be extracted from a warm well at a temperature of 15–17°C. It transfers its heat content via a heat exchanger to a heat pump. The cooled groundwater is infiltrated in the cold well at a temperature of 6–7°C. The heat pump transfers the low temperature heat content to a temperature of 40–55°C, while additional equipment can increase the temperature further for heated tap water purposes. In the summer the flow of the groundwater circuit is reversed and cold water from the cold well can be used for cooling purposes. The CO_2 reduction can be substantial compared to traditional heating and cooling of a building, and 50–70% reductions are reported. An underground aquifer can also be used to store thermal energy recovered from sun collectors, surface water, sewer systems and even from drinking water.

A large aquifer is installed at the Stockholm airport Arlanda. Since 2009 Arlanda has the world's largest thermal energy storage unit. All cooling of airport buildings, including the terminals, will come from the aquifer. Arlanda consumes as much energy as a city of 25,000 people. In the winter when it is needed to melt the snow in aircraft parking stands and pre-warm the ventilation air in buildings the aquifer provides heating. The aquifer will reduce the airport's annual electricity consumption by 4 GWh and its district heating consumption by around 15 GWh – equivalent to the energy consumed by 2000 single-family homes (Swedavia, 2014).

The city of Amsterdam has adopted an environmental policy with several aquifer thermal energy storage projects, the Aquifer Thermal Energy Storage (ATES) systems. For example, a data center in Amsterdam has drilled down into a vast underground aquifer to regulate temperatures in the summer and winter. A thesis by Caljé (2011) considers questions relating to heterogeneity, salt mixing, thermal pollution, cooperation, and arranging of ATES systems. This is done using a flow and transport groundwater model, which takes into account density and viscosity variations, as a result of temperature and salinity changes. Bonte *et al.* (2011) have used data from an ATES system located 570 m from a public water supply well field in the south of the Netherlands to investigate the relation between production of renewable energy with an ATES system and the production of drinking water. The authors show that the groundwater circulation by the ATES system can impact chemical groundwater quality. Still, the observed concentration changes are sufficiently small to keep groundwater suitable for drinking water production. Microbiological results showed that the ATES system introduced faecal bacteria in the groundwater and stimulated the growth of heterotrophic micro-organisms. At the studied site this forms no hygienic risk. However, a further degradation of either chemical or microbiological groundwater quality may necessitate additional water treatment which raises the energy requirements.

19.2 SURFACE WATER

Surface water can be a source of both cold and warm water. A deep lake can serve as a cold water source for cooling buildings and shallow water can collect heat from the sun that can be used for heating elsewhere. The principle to use cold water from deep lakes is straightforward. Cold water is pumped from the lake via a cooling network into an office building. In a heat exchanger the cold water from the lake is transferred to the water in the cooling network and provides cooling of the office building. Systems based on this principle are in use in several cities. The idea is similar to district heating and is economical over limited distances and for a high user density in the served area.

The precondition for the efficient operation of district cooling is the access to a cold source. In Helsinki, Finland, the district cooling system uses sea water directly. During summer the waste heat from CHP power generation plants is used to run absorption refrigerators. It is estimated that more than 80% of the district cooling production is based on energy that otherwise would be wasted (Riipinen, 2013). In Toronto, Canada, Lake Ontario is the cold source, where water at 4°C is collected 5 km offshore at 83 m below the surface (Toronto, 2015).

The profitability of the district cooling solution depends on several parameters, in first place access to land and the right differential between winter and summer temperatures. Under suitable conditions snow cooling can drastically contribute to the reduction of electric power demand. A solution recently developed in Sweden is the accumulation of winter snow in shadowed areas, to be used again as a cold source during summer (Snowpower, 2015). Snow cooling is also used at the Oslo airport in Norway (Oslo airport, 2015). Clearing snow on the runways and taxiways the airport can collect 22,000 m^3 snow during the winter season to be used for cooling the passenger terminal in the summer. When the system is operating, the snow will cover a cooling need of 2 GWh in the terminal. The snow storage is a 8000 m^2 watertight basin placed in the airport area. It is isolated to prevent the snow from melting before the summer use.

The energy savings and the carbon emission savings are substantial. One example from Amsterdam is given by van der Hoek (2011). With individual cooling machines in the buildings the electrical energy consumption was 29,200 MWh/year and the corresponding CO_2 emission 23,900 tons/year. With a central cooling machine combined with water from a lake the corresponding numbers were 4,900 MWh/year and 4,000 tons/year respectively, reductions of 83% for both energy requirement and carbon emissions.

19.3 HEAT RECOVERY FROM WASTEWATER

The thermal energy in wastewater is significant, since heated water is mostly mixed in the used drinking water that leaves the customer. Statistics from Amsterdam gives a clear message, according to Table 19.2. Around 54% of the drinking water that is used in a household is heated. Wastewater contributes to 40% of the heat loss from a modern house. This corresponds to an annual average loss of 8 GJ/house (≈2200 kWh/house), equivalent to an emission of 450 kg CO_2.

Table 19.2 Typical water temperatures in an Amsterdam home.

Location	Temperature °C
Bathing and shower	38–40
Tap water outlet from house	10–55
Dishwasher, washing machine	40
Average temperature of water leaving the house	27

Sources: van der Hoek (2011) and Hofman-van Loosdrecht (2009).

In the individual house the thermal energy can be recovered by using heat exchangers. This is already applied for shower water in some new houses. In Hamburg, Germany thermal energy is recovered at a housing estate level. Heat exchangers are installed directly in the sewer and recover thermal energy from the wastewater. 215 houses are heated with this recovered energy. Hamburg Wasser claims a reduction in greenhouse gases in this specific installation of 700 ton CO_2-eq/year (Augustin, 2011).

Another example is from an indoor swimming bath in Sweden (city of Oskarshamn). Warm water from showers is led to a heat exchanger that will pre-heat the incoming cold water to the showers. The temperature of the incoming cold water was raised around 7°C in the period May to September and around 8 kWh/m^3 was saved.

It is of course essential to use the heat content of wastewater in the wastewater treatment plant. Since the growth rate of microorganisms increases with the temperature it is favourable for the biological treatment that the heat content of the wastewater is extracted after the treatment. The Henriksdal wastewater treatment plant, serving central and southern Stockholm has an average flow rate 250,000 m^3 per day. Seven heat pumps of totally 225 MW extract the effluent wastewater heat and deliver the thermal energy to the Stockholm district heating system. The heating energy corresponds to the need for 95,000 two-bedroom apartments. The generated cold water is used for district cooling (www.stockholmvatten.se).

Hawley-Fenner (2012) describe how much heat could be recovered from wastewater treatment plants under UK climatic conditions. The results show a significant potential for thermal energy recovery from wastewater. Thermal energy recovery for district heating applications has been shown to have the greatest carbon reduction potential.

19.4 HEAT FROM DRINKING WATER

Drinking water offers opportunities for energy recovery, chemical energy as well as thermal energy. Chemical energy concerns the use of methane that can be present in groundwater.

Recovery of methane from groundwater during drinking water production is under development at the moment at Vitens, one of the drinking water companies in the Netherlands.

The water company Waternet in Amsterdam uses surface water as source for drinking water. Also here opportunities are present. Due to climate change the temperature of the surface water is rising, and the increase in temperature may be used to recover thermal energy from drinking water, produced from surface water.

Mol *et al.* (2011) describe how public water utilities can substantially contribute to the production of sustainable energy, especially by making use of heat, cold and biogas from the water cycle. Public water utilities have the opportunity to both regulate and enter the market for energy from water.

19.5 CHAPTER SUMMARY

Water has an extremely high specific heat capacity. This is the reason why water can store so much thermal energy that can be used both for heating and for cooling purposes. As the attention to energy issues is increasing more and more water sources are getting used for thermal energy extraction. Experiences have been gained from using thermal energy in groundwater and surface water as well as drinking water. The water leaving a home is much warmer than the water entering the building. All this extra thermal energy can be used and significant savings of energy have been reported.

19.6 MORE TO READ

Heat recovery contains a lot of practical and operational issues. Therefore it is beneficial to explore the Internet (Wikipedia) and commercial companies working with heat recycling, heat recovery and cooling systems.

20 Desalination

> *Kissing is like drinking salt water – you drink and your thirst increases.*
>
> Facebook.

Most of the human population is located in coastal areas and small island developing states. Actually two out of three of the world's largest cities concentrate along the coasts. The coastal population is expected to reach about 1.6 billion people in 2015, about 22% of the total population. This increasing coastal population – in combination with the climate change – will put a lot of pressure on coastal resources. Uncontrolled release of wastewater creates a threat to the water quality of coastal zones. This in turn will threaten fisheries and tourism.

Seawater is the only long-term, completely reliable source of drinking water for future generations. Desalination is a process that separates dissolved minerals and impurities from seawater or other salty water. Evaporation of water over the oceans in the water cycle is a natural desalination process. Desalination is often the only viable option for providing safe drinking water in many arid coastal regions. Desalination technology was established already in the 1950s. Thermal desalination processes – based on evaporating water and collecting the condensation – were already well commercialized long before desalination by reverse osmosis (RO) was developed. Historically, commercial desalination plants operated using thermal processes in locations where energy was plentiful or inexpensive and freshwater was scarce. Consequently, desalination provides substantial volumes of drinking water in areas of the Middle East with abundant energy resources.

Desalination is an energy intensive water supply technology, as noticed in Table 15.2. Consequently, desalination is an appropriate option only when there are no other sources or the cost of energy for transporting water is very high.

20.1 THE GLOBAL DESALINATION PICTURE

In 2011 some 75 million m^3 of desalinated water was produced every day. The increase has been very rapid, from about 25 million m^3 in 2006 and 60 million m^3/day in 2010. The production of desalinated water corresponds to 0.5% of global freshwater use. The production is expected to rise to almost 100 million m^3/day in 2015. In early 2012 there were about 16,000 desalination plants worldwide operating in more than 150 countries, providing water for about 300 million people (UN WWDR, 2014). Desalinated water requires around 75 TWh/year, which is about 0.4% of global electricity consumption (IRENA, 2012c). It is apparent that desalination technology may be suitable for supplementing water supplies for domestic and certain industrial users in middle and high income regions near the coast. However, it is currently not an affordable alternative for the poorest countries, for agriculture, consuming a lot of water, or for consumption at a distance from the plant due to transportation costs. Desalination is used in most countries in the world today. The largest desalination production is found in Saudi Arabia, USA, UAE, Kuwait, Libya and Japan. Middle East has more than half of the world capacity, mostly in Saudi Arabia where desalination plants meet 70% of the drinking water needs. The US has an abundant supply of brackish groundwater in saline aquifers. Over the past two decades, the use of treated wastewater has been growing at 15% annually and the use of brackish water at 10% annually. In some locations, the cost of producing desalinated water is becoming comparable to the cost of finding and transporting in freshwater (Texas Water Summit Report, 2012).

The total cost of producing 1 m^3 of fresh water from the sea including energy, capital and all operational costs is reported to have dropped below is US$ 0.5 (IRENA, 2012c). This means that with current desalination capacity each one of the 7 billion people of the world could get 10 liters of clean water for around 1 US cent. The price of desalinating water continues to fall and it is estimated that it may cost no more than freshwater extraction by 2020 in some parts of the world. Energy cost is the principal barrier. The source is not always seawater, as shown in Table 20.1. The primary users of desalinated water are listed in Table 20.2.

Table 20.1 Potable water sources (globally) for desalination.

Desalination from	Percent
Seawater	59
Brackish water	21
River water	9
Pure water for industrial applications	5
Wastewater for reuse	<5

Source: Wikipedia.

Table 20.2 Primary users of desalinated water.

Primary users	Percent
Municipalities	63
Industry	26
Power industry	6
Agriculture	2
Tourism[1]	2
Military	1

[1] Municipalities probably include a lot of tourism.
Source: Wikipedia.

20.2 PRINCIPAL METHODS FOR DESALINATION

The two most widely used desalination technologies are reverse osmosis (RO) with almost 60% of installed capacity and multi-stage flash (MSF) distillation at 26%. The RO process is electric power driven while the MSF process is thermally driven.

Today – excluding those in the Gulf countries, North Africa, China and India – the majority of desalination plants constructed are based on RO technology. The basic principle of RO is simple. Pump the salty water at high pressure through permeable membranes or filters. Sometimes the water is passed through several stages of membranes before it is declared a final product. Naturally the quality of the water depends on the pressure, on the membrane and of the salt content of the water. RO can also remove unwanted contaminants such as pesticides and bacteria.

In distillation the water has to be heated and evaporated to separate out the dissolved minerals and subsequently cooled. Distillation plants generate less waste than RO systems and no filters or membranes can be clogged. There are three basic principles of distillation. Many plants apply a mixture of the technologies:

- *Multistage Flash distillation (MSF)*: the water is heated and the pressure is decreased so that the water 'flashes' into steam;
- *Multiple Effect Distillation (MED)*: the water passes through a number of evaporators in series. Vapour from one series is subsequently used to evaporate water in the next.
- *Vapour Compression (VC)*: the feedwater is evaporated and the vapour is compressed. The heated compressed vapour is then used as heat source to evaporate additional water.

MSF will require much more energy per m^3 of freshwater (typically 12–15 kWh and sometimes as much as 25 kWh). Two types of energy are required for the operation of a thermal desalination plant. The first is low temperature heat, which is the main portion of energy input. The second is electricity, which is used to drive the system's pumps. The RO process requires electrical energy to supply the high pressure pump, typically 3–5 kWh.

An alternative to the current desalination methods is a low-energy desalination method based on a microbial desalination cell (MDC) technology. It has been created by modifying a microbial fuel cell (MFC), a device that uses exoelectrogen to convert wastewater into clean water and electricity. The MDC requires no external energy source. The main difference between this technology and a conventional MFC is that the MDC uses two membranes rather than one (or none). Salty water is placed between an anion exchange membrane and a cation exchange membrane. When bacteria on the MDC's anode produce current and protons, the salty water's anions migrate through the membrane to the anode, and the cations are drawn to the cathode. In addition to producing power, the MDC can remove 90% of the salt from water with up to 35 grams of salt per liter, which is roughly the equivalent of seawater. Logan (2008) presents a comprehensive view of microbial fuel cells (MFC). Mehanna-Logan (2010) and Logan (2012) have reported recent advances in MFC technology.

It is obvious that low-energy desalination would benefit many parts of the world where clean water for drinking, washing and other uses is in scarce supply.

20.3 MEMBRANE SEPARATION

In membrane filtration a substance is physically separated by means of a semi-permeable membrane. The process is driven by using for example pressure across the membrane. This force pushes the smallest molecules in a given solution through the membrane and keeps back the larger molecules. Pressure driven membrane separation can be divided into four different types

- *Micro filtration* (MF) screens particles from 0.1 to 0.5 microns (10^{-6} m);
- *Ultra filtration* (UF) screens particles from 0.005 to 0.05 microns;

- *Nanofiltration* (NF) screens particles from $0.5 \cdot 10^{-3}$ to $1 \cdot 10^{-3}$ microns;
- *Reverse osmosis* (RO) ranging molecular size down to about 1 Angstrom (10^{-4} microns).

MF can remove suspended solids, high molecular weight species, bacteria, pathogens such as Cryptosporidium and Giardia in drinking water. The Cryptosporidium is a parasite that commonly occurs in lakes and rivers, particularly when these water systems are contaminated with sewage or animal waste. The MF and UF techniques do not require any chemicals to inactivate the microbes.

Membrane technology has a huge impact on water purification.

Water purification by UF can remove macromolecules, colloids, viruses, proteins and pectins. The UF does not remove all the natural minerals, such as calcium (Ca^{2+}) or – more important – the salinity of seawater.

NF can remove small molecules and polyvalent ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), while RO is needed to remove soluble salts, smaller ions, colour and low molecular weight species.

Another parameter that distinguishes the four types of membrane filtration from one another is the pressure under which they normally operate. The flux (the capacity of purified water, permeate, measured in liters per m^2 of membrane per hour) depends on the feed pressure. MF and UF need comparably low pressures, while NF and RO require much more. Typically NF would need 10–40 bar, while RO would require 15–70 bar. Above the optimum pressure clogging of ‘pores’ occurs and the membrane is compacted.

20.4 REVERSE OSMOSIS

RO dominates the desalination technology and the application of RO is expected to increase tremendously during the next decades. In order to understand the basics of RO, let us first look at osmosis, which is the basis for RO. Natural osmosis governs how water transfers between solutions with different concentrations. It is the basis for the way in which human skin and organs function, and how flora and fauna maintain water balance. The osmosis process can be explained when there is a semi-permeable barrier such as a membrane located between two solutes with different salt content, Figure 20.1.

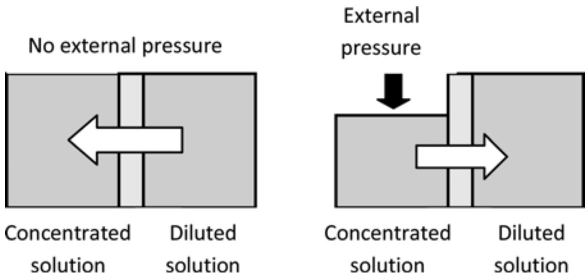


Figure 20.1 Schematic of osmosis (left) and reverse osmosis (right). The arrows denote the water flow direction.

In natural osmosis the water tends to flow from a solution with a lower concentration to a solution with a higher concentration, as long as no external pressure is applied. When an external pressure (Δp) that exceeds the osmotic pressure difference ($\Delta\pi$) is applied to a concentrated solution, clean water will be displaced out of the concentrated solution, while salts will remain in the more concentrated solution. Theoretically, salts should not pass through the membrane. In practice, however, salt leakages occur as a result of diffusion.

The osmotic pressure π is given by the van't Hoff equation:

$$\pi = c \cdot R \cdot T$$

where c is the ionic molar concentration, R the gas constant and T the temperature in Kelvin. This shows that the required pressure increases with the salt concentration.

The water flow is proportional to the pressure difference:

$$J_w = C \cdot (\Delta p - \Delta\pi)$$

Where J_w is the flux (l/m^2 membrane per hour) and C a constant. A small part of the dissolved substance also goes through the membrane with the water. Some 2% of common salt (NaCl) may go through the filter in RO. The osmotic pressure for seawater with 3% salt is of the order 17–18 bar. This means that a RO system for sea water only begins to produce water when a pressure higher than the osmotic pressure is achieved. Brackish water needs less energy since the osmotic pressure is lower.

Reverse osmosis is a key technology for seawater desalination and water reuse.

20.5 DESALINATION USING REVERSE OSMOSIS

The first successful demonstration of a RO membrane that worked was made in 1959. This marked the beginning of desalination by RO. In a full scale system the RO elements are encapsulated in pressure vessels. A number of vessels are mounted on a RO rack that can be operated in parallel or in series. Since RO membranes cannot tolerate particulate matter of any kind, they require pre-treatment consisting of different types of filtration and/or separating processes as well as feedwater conditioning by chemicals.

The RO reject carries significant energy that can be returned back to the process, thus minimizing the overall energy demand for the RO process.

The desalination techniques using RO – either brackish water RO (BWRO) or seawater RO (SWRO) – are now having the greatest number of installations around the world. It is predicted that the RO applications will grow by 10% per year.

A major factor that has prevented the widespread use of membrane desalination has been its high energy demand. The largest power consumer is the high-pressure pump. The energy demand is affected by the water salinity, the water temperature and the system recovery (the ratio of permeate – the low concentration product water – to feed water). The energy requirement in the RO process increases with increased salinity. Lower electrical energy intensities in RO systems are often achieved by using energy recovery systems.

The development of energy recovery exchangers of different configurations can recover more than 90% of the concentrate stream. Other developments include improved materials such as thin film composite membranes as well as advances in design and operation of RO plants. Important parts of the improvements include the introduction of low pressure MF and UF filters for pre-treatment.

Desalination costs may come from two areas, treatment and concentrate management. Treatment costs have decreased significantly due to higher performing membranes, less expensive membrane modules, energy recovery devices and increased competition. In contrast, the costs of concentrate management depend very much on the location. Locating the desalination plant at the ocean gives much more flexibility than locating the plant inland. The inland desalination plants can be used to water reuse and drinking water production from wastewater where traditional sources are inadequate. For the inland plants the disposal options have to be carefully considered. The primary environmental concern with disposal of concentrate to surface water, to the sewer or by land application is salt loading to receiving waters, whether surface water or groundwater.

20.6 NEWER OSMOSIS TECHNOLOGIES

Forward osmosis (FO) is a relatively new process – still based on osmosis – that can offer significant progress. FO can achieve a high osmotic pressure when using ammonia or carbon dioxide or other ingredients in the 'draw' (salt) solution. FO can be used to deliver drinking water for residential communities and island applications using relative high salt-concentration water such as seawater. FO can also be used to treat wastewater for reuse. The draw solution has a higher osmotic potential than the dirty feedwater side. This naturally pulls the water from the dirty feed side through the membrane, which rejects organics, minerals and other solids. The result is only clean water moving through the membrane. FO allows for a high degree of separation using relatively little energy.

The FO process can be combined with high pressure digestion in order to recover the salt after the FO process. The digestion process can offer local energy recovery because of fermentation.

Pressure retarded osmosis (PRO) uses differences in osmotic pressure of different solutions to generate osmotic power. This process can take place where a river meets the sea and where wastewater is discharged into the sea or ocean. PRO uses osmotic pressure to generate power where two solutes with different salt concentrations are available. The higher difference between the salinities of two waters creates a higher osmotic gradient, which helps achieve higher PRO process efficiency. Any delta of a river, where freshwater flows into seawater, could be a good candidate to generate osmotic power for PRO. The PRO process is under development but has already proven to generate enough energy to compensate for the additional energy required by the RO process to overcome natural osmosis. Since November 2009 the first osmotic power plant started operating in Norway using Tofte River water to produce clean osmotic power (National Geographic, 2013). Still the power is minute, only 2–4 kW, but the Norwegian Center for Renewable Energy (SFFE) pegs the global potential of osmotic power to be huge.

20.7 ENERGY REQUIREMENT FOR REVERSE OSMOSIS

The large energy requirement for desalination – more than ten times the traditional surface water treatment – contributes to greenhouse gas emissions when using fossil fuel-generated electricity. Therefore it is important to determine where this energy is used in the process. Large amounts of energy are needed to generate the high pressure that forces the water through the membranes.

As noted in 20.2 current RO methods use 3–5 kWh to produce 1 m^3 of desalinated seawater (California reports 3.6–4.5 kWh/m^3), while brackish water will require less energy, 0.5–2.6 kWh/m^3. However, there is a potential for increasing the efficiency. The theoretical limit for RO is around 1 kWh/m^3, while the practical limit seems to be around 1.5. Some sources say that 1.5–2 kWh/m^3 is achievable to desalinate seawater. The energy loss in the separation is the energy needed to push the water through the membrane. This can be reduced by designing a thinner membrane. There has been a tremendous development in membrane materials. A layer will have typically a pore diameter of about 150 Angstrom. The thickness of a polyamid layer acting as the salt barrier can typically be around 2000 Angstrom.

A key focus in desalination is around recovery of energy, reuse, and minimizing the amount of mechanical energy required in the separation unit. In a typical desalination plant about half of the water pumped into the system is discharged as brine waste. This ratio is often determined by the salinity of the feedwater, the temperature of the water and the quality requirements of the permeate. Obviously a lot of power is required to create the pressure that will force the water through the system. To decrease the energy requirement the waste stream is pressurized and is used to pressurize the seawater that is coming into the system. In this way it is possible to recover some 95–99% of the energy.

The economy for desalination depends on the location. For affluent areas in proximity of oceans the desalination alternative is generally very positive. However desalination may not be the solution for places that are poor, deep in the interior of a continent or at high elevation. In Chapter 15 we noted the high cost for water pumping in some places (Table 15.5). The costs for pumping were discussed also in Chapter 16.1. Therefore the cost of desalination should be compared with the cost of treating freshwater and then transport it a long distance. In a high place like Mexico City the transport cost is high. In other places like Beijing and Bangkok the desalination and not the transport would be the dominating cost. For coastal cities, desalination is increasingly viewed as an untapped and unlimited water source. Generally water reuse can sometimes be an alternative to desalination or transportation of water over long distances (Pearce, 2012).

The cost for desalinated water is discussed vigorously, not the least in California, where desalination has been subject of a lot of political debate for a long time. Now the Carlsbad desalination plant is under construction (see 20.9). The desalinated water is estimated to cost about US$ 1.6/m^3. This cost is estimated to be about double that of water obtained from building a new reservoir or recycling wastewater, according to a 2013 study from the state Department of Water Resources (San Jose Mercury News, www.mercurynews.com/science/ci_25859513). The cost of desalinated water is at least four times the cost of obtaining 'new water' from conservation methods – such as paying farmers to install drip irrigation, or providing rebates for homeowners to rip out lawns or buy water-efficient toilets.

20.8 SUPPLYING POWER

All kinds of electrical power sources can of course be used to supply a desalination plant with energy. Considering the high power demand and the potential carbon footprint, however, it is highly motivated to use renewable energy (RE) to power the desalination. Interesting RE sources are wind, biomass, wave and solar PV systems. Also solar thermal, geothermal, hydroelectric and nuclear power are considered for powering desalination plants. Solar-powered water pumping can raise clean water from depth and transport it to where it is needed, and already does so in many locations.

The production of electricity and water can be combined, for example in so called hybrid desalination plants. This kind of plants is found in the Middle East, where there is very little water available and where desalination is likely to expand. The Fujairah plant in the United Arab Emirates and the Shoaiba plant in Saudi Arabia are typical hybrid desalination plants, where desalination is integrated with thermal power generation, which improves efficiency and lowers the electricity cost of desalination processes. Steam from the power plant is used as the heat source for the desalination process.

Many renewable and alternative energy sources have an intermittent production, such as solar PV and wind. Often, however, peak production times for solar and wind energy align with peak demand periods for water pumping and treatment. If there is an excess power production this energy can be stored as fresh water buffer. In other words, water can serve as important energy storage, just like in hydropower.

In many parts of the developing world there is plenty of both brackish water and solar energy. The use of solar energy to supply local desalination of brackish water with power is an interesting option where potable water is scarce. Jordan, Israel, the Palestinian Authority and the USA, in a joint effort, have undertaken such an activity in the Middle East.

Some large water supply systems transport water long distances from an inland area to a coastal area. Southern California gets water from the Colorado River (see Map 10.5) and Tripolis (at the Mediterranean coast) in Libya is supplied by water from the aquifers down south in the Sahara desert. Why not use desalination in the coastal areas and use the inland water where desalination is not an alternative?

Environmental impacts, such as greenhouse gas emissions and the by-products of desalination require careful consideration to balance water security with sustainability. Using renewable energy sources such as solar, wind and biogas from wastewater can help to decouple carbon intensive energy production and the growing need for water desalination.

20.9 DESALINATION PLANTS – SOME CASES

The energy requirement of a RO plant can be exemplified by the first desalination plant in the UK, the Beckton desalination plant, opened in June 2010. The plant is located in the tidal area of River Thames, downstream of London. The water quality parameters vary in a 12-hour cycle due to the sea tides. Therefore the plant abstracts raw water from a tidal area during a three hour period prior to each low tide, when salinity is lower. Then it can maintain the raw water salinity in the range of brackish water. The production is about 150,000 m^3/day. The energy consumption for Beckton has been reported as shown in Table 20.3 (yearly average):

Table 20.3 Energy consumption in the Beckton desalination plant, UK.

Operation	Energy kWh/m^3
Raw water abstraction	0.16
Pretreatment	0.36
Reverse osmosis	1.39
Treated water pumping	0.20
Miscellaneous	0.18
Total	2.28

Source: Zorilla (2011).

- *Perth, Australia*: The city of Perth started the push for desalination in Australia (see Map 7.2). The first plant is located in Kwinana, 40 km south of Perth, and was put into operation in 2006 and provides 130,000 m^3/day, which corresponds to some 17% of the city's water supply. The plant is the largest in the world to use renewable energy. An associated wind farm of 82 MW capacity provides the energy and also produces surplus energy into the grid. A second desalination plant has been started in 2011, in Binningup some 150 km south of Perth, with a 50,000 m^3/day capacity in the first stage. Discharging the concentrate from the desalination plant is favourable. There are strong winds and various currents in the Indian Ocean that will provide a powerful mixing, which is favourable for the marine environment when discharging the concentrate from the desalination plant (Molina *et al.* 2009; Stedman, 2010).
- *Australia*: Large-scale seawater reverse osmosis plants now contribute to the domestic water supplies of several major Australian cities including Adelaide, Melbourne, Sydney, Perth and the Gold Coast. The carbon footprint of the energy supply is problematic due to Australia's coal-based energy supply. However, like in Perth the desalination plant in Sydney is powered by 100% renewable wind energy. It can supply up to 250,000 m^3/day which is up to 15% of all water needs. Poussade *et al.* (2011) have compared desalination with water reuse in Queensland, Australia.
- *Beijing, China*: In Beijing desalinated water will be available before 2015 (China Daily, 10 Nov 2011). Water from the Bohai Bay will be pumped 230 km to Beijing. The first desalination project in China was completed in October 2011 and produces 50,000 m^3/day. The plans are to provide almost 3 million m^3/day to Beijing in the future.
- *Israel*: Since the Ashkelon plant was opened in 2005, Israel has opened another three desalination plants. Roughly 35% of Israel's drinking-quality water now comes from desalination. That number is expected to exceed 40% in 2015 and hit 70% in 2050. The Sorek desalination plant, located roughly 15 kilometers (10 miles) south of Tel Aviv, provides up to 26,000 m^3 of potable water per hour or 620,000 m^3/day. At full capacity, it is the largest desalination plant of its kind in the world. Once unthinkable, given Israel's history of drought and lack of available fresh water resource, with desalination, Israel can now actually produce a surplus of fresh water. In 2014 the plants in Sorek, Hadera, Palmahim and Ashkelon were desalinizing water for less than US\$0.40/m^3. Still it has to be remembered that the plans require huge amounts of energy, consuming roughly 10% of Israel's total electricity production.
- *California*: In Carlsbad, California, north of San Diego, the largest seawater desalination plant in the Western Hemisphere is under construction. The facility, when finished in 2016, will be able to provide 190,000 m^3/day of freshwater. A desalination plant in Santa Barbara, California uses 50 million kWh for 9.25 million m^3 of water, or 5.4 kWh/m^3 (De Villiers, 2001). To move the same amount of water from the Colorado River (Map 10.5) over the mountains and the long distance, takes 15–26 million kWh, or 1.6–2.8 kWh/m^3. Another two smaller plants already operate in California, and 15 more have been proposed (2014) along the coast from Los Angeles to San Francisco Bay. California is suffering its third year of drought (San Jose Mercury News, www.mercurynews.com/science/ci_25859513).
- *Saudi Arabia:* The Saudi government has allocated US\$ 4.4 billion in 2014 alone for desalination projects. The world's largest desalination plant, the Jubail Plant located at the Persian Gulf, was put into operation in 2014 and can produce more than 1 million m^3

freshwater per day. It has a 2,745 MW power capacity and is the world's largest integrated water and power facility (www.bloomberg.com/news/2014–04–23).

- *Republic of Korea*: The Center for Seawater Desalination Plant (CSDP) was established in 2006 and launched a most ambitious R&D project SEAHERO (seawater engineering and architecture of high efficiency reverse osmosis) in 2007. The project is coordinated by the Gwangju Institute of Science & Technology (GIST). Over 500 researchers from 16 universities are contributing. The funding is US $165 million for the period 2007–2012. One of the most important technical targets of SEAHERO is the scale-up of SWRO systems for economies-of-scale (Kim *et al.* 2009; Kim, 2013). Korea is now having its first large seawater desalination plant up and running, located in the city of Busan.
- *Singapore*: In September 2005 opened its first desalination plant SingSpring. The plant can produce 136,000 m^3/day. A second and larger desalination plant, the Tuaspring Desalination Plant, has a capacity of 318,500 m^3/day. Today, desalinated water can meet up to 25% of Singapore's current water demand (www.pub.gov.sg).

20.10 CHAPTER SUMMARY

The production of fresh water using desalination is increasing at an impressive rate, from 25 million m^3/day in 2006 to expected 100 million in 2015. Progress in membrane technology has contributed to make filtration affordable, and reverse osmosis is gaining quickly in implementations all over the world.

Current RO methods use 3–5 kWh to produce 1 m^3 of desalinated seawater and there is a potential for increasing the efficiency. The practical limit for RO seems to be around 1.5 kWh/m^3. A lot of operating experiences have already been gained from large installations around the world.

20.11 MORE TO READ

A good introduction to desalination is obtained via Wikipedia-desalination (2012) and in DOW (2011). Burn-Gray (2014) present a deeper analysis of reverse osmosis. Drioli *et al.* (2011) describe the basics of RO and desalination. Results and experiences are shown from a three year project funded by the European Commission within the 6th Framework Program. The United Nations Environment Programme (UNEP) developed and released a new guidance document on desalination in cooperation with the World Health Organization (WHO) (Lattemann-El-Habr, 2009). Tarnacki *et al.* (2011) have compared different desalination techniques using life cycle assessment. Forward osmosis is described for example, in Lutchmiah *et al.* (2011).

Bundschuh-Hoinkis (2012) discuss the applicability of renewable energy for freshwater production, both various barriers and how to overcome the hurdles.

21 Customer behaviour – demand side management

> *The chief necessities of human life are water, fire, iron, and salt, flour, honey, and milk, the juice of the grape, oil, and clothing.*
> The Old Testament, Ecclesiasticus (The Wisdom of Jesus Son of Sirach), 39:26

A British study suggests that water users are generally unaware of their own consumption (as noted in Chapter 8.4) and that individual perceptions of changes in behavior are constrained by habit and lack of knowledge (Water 21, 2011). In the study it is suggested that major actors such as governments and water companies now need to step in to change habits. The public has an important role in reducing demand for water. As water shortages become critical, the public should not only be guided to make changes but also form a big part of the decision making process. The public should be made aware of the services that the water companies and power companies can provide; providing fundamental information regarding the water, wastewater, and the energy systems; specific information about how much water and energy people use in their daily activities; and practical guidance on how to save water and energy in the home.

Our attitudes to both water and energy need to be changed. Neither resource is infinite and we all have to become aware of how we as users and customers can change our consumption patterns.

21.1 DOMESTIC WATER USE

Water usage has an energy cost and both energy and water uses have to be sustainable. Recent droughts have put the focus on the water consumption in some countries. It is apparent that the water consumption varies a lot between different countries. In Figure 8.2 the specific water consumption from 104 cities around the world is shown. The consumption in the 104 cities varies from 0.34 to 650 liters/capita/day while the total charge for drinking water varies from 0.015 to 3.13 US\$/m^3. Some national comparisons are given in Table 21.1. Data from other sources are given in Figure 8.1 and the different values should be noted.

It is true that the natural conditions are quite different. Still these figures often reflect the habits and sometimes misuse of water. Naturally the price of water has a role to play. In general, the price paid by the consumer has a direct influence on the amount that is used. In the USA the average household spends 0.006% of the income on water. The corresponding numbers for UK are 0.013%, for Pakistan 1.1% and for Tanzania 5.7%. It is most often true that poor people pay more. While the average USA household pays around 0.5 US$/m^3 and a German pays 1.9 US$/m^3 poor people often depend on informal vendors. A typical water price in Dhaka, Bangladesh is 0.4 US$/m^3, in Phnom Penh, Cambodia 1.6 US$/m^3 and in Manila, Philippines 4.7 US$/m^3 (Clarke-King, 2006). Curbing demand is cheaper, faster, and ultimately more beneficial to individuals than increasing supply. Conservation of water saves both energy and water.

Table 21.1 Water consumption in some countries.

Nation	**Water use liters/cap/day**[a]		
	Domestic	**Agriculture**	**Industry**
USA	600	1900	2100
Australia	500	2600	340
Canada	800	480	2800
China	85	910	345
Germany	190	310	1060
The Netherlands	80	460	820
India	140	1500	95

[a]See Appendix 1 for conversion of units.

Sources: Voinov-Cardwell (2009), Clarke-King (2006).

21.2 WATER CONSUMPTION AT HOME

The water consumption is dramatically different around the world. Here we give examples from single family homes in the USA and in Australia. In the Table 21.2 it is confirmed that there is a significant outdoor use of water in many US homes and this consumption can be reduced drastically.

Table 21.2 Water use in single family homes in 12 monitored cities in the US and average values for Australia.

Water use	**US liters/cap/day**	**US %**	**Australia liters/cap/day**	**Australia %**
Taps	39	19	21	13
Shower	42	20	46	29
Bath	6.8	3	8	5
Laundry	54	26	40	25
Dishwasher	3	1.5	3	2
Toilets	63	30	42	26
Total indoor	208	100	160	100
Leaks	30			
Outdoor	313			
Total	551			

Sources: US: adapted from Novotny (2011), AWWA RF (1999) and Asano *et al.* (2007); Australia: adapted from Kenway *et al.* (2008), Figure 10.

There is a great potential for water savings in the home by using better appliances. This relates directly to energy savings.

21.2.1 Simple water saving rules indoor at home

In Chapter 8.4 we discussed that information to the customer is crucial if water and energy savings can be successful. Some simple rules for the water savings at home can be mentioned:

Toilets: Table 21.2 shows that the toilet is a large consumer of water. The average person in an industrialized country will flush the toilet little more than 5 times per day. This means 140,000 times during a lifetime. Then it makes a huge difference if the toilet uses 20 liters per flush or 4 liters per flush. There is a huge potential to save water by using low flush toilets. Then simple rules make a difference. Whenever the toilet is used as a wastebasket water is wasted unnecessarily.

Leaking faucets: a small drip from a worn faucet washer can waste tens of liters of water per day. Larger leaks can waste hundreds of liters.

Faucets: all household faucets should be fit with aerators. This single best home water conservation method is also the cheapest!

Shower: use a low-flow shower head and take shorter showers.

Dishwasher and washing machine: use the dishwasher and clothes washer for only full loads. Washing clothes at 30°C saves energy, and today's detergents wash very well at low temperatures. A modern dishwasher needs more than 2 hours to complete the dishwashing. New machines use much less water, only some 10 liters, compared to old dishwashers that can use as much as 50 liters. It takes a longer time to wash the dishes with less water. The machine heats the water to about 55°C and naturally it takes less energy to heat 10 compared to 50 liters. The extra energy that the dishwashers need to operate longer is much less than the energy savings for heating. The same principle is true for washing machines.

Drinking water: keep a bottle of tap water in the fridge.

Outdoor use: a garden hose can use more water in an hour than a family of four uses in a day. Using a watering can instead of a hose saves water. Collecting rain saves the mains water and the energy to treat it.

Measurements are important. Water metering encourages a more efficient use of water in the home. It has been observed in many places that water savings from household metering can be significant. The water meter should also be used to detect leakages. The household water meter can be recorded before and after a 2–3 hour period when no water is being used. If the meter does not read exactly the same, there is a leak. In the future the demand would further benefit from smart meters that could provide information against benchmarks for per capita consumption and cost.

Simple rules of behaviour at home can save huge volumes of water. Measurements are crucial to raise the awareness of the customer.

21.2.2 Bottled water

There has been an explosive growth of bottled water during the last decades. This has happened also in countries where the tap water fulfils strict quality criteria. The global sales volume of bottled water is a US$ 60 billion business. One estimate is that the global consumption is

230 million m^3 of bottled water (www.bottledwater.org). The largest consumers are shown in Figure 21.1.

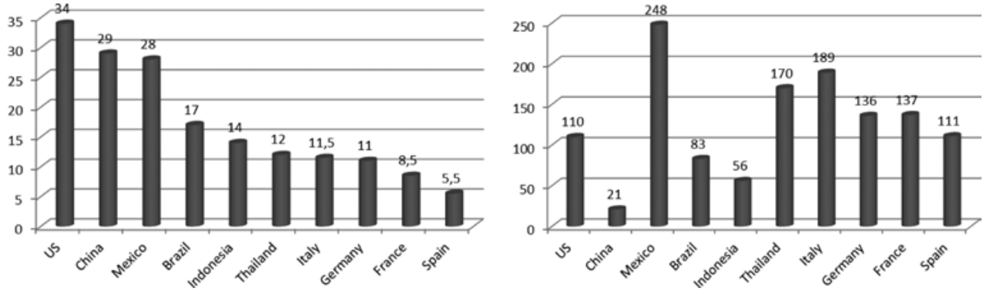


Figure 21.4 The largest bottled water consumers in the world in 2011. The left diagram shows the total consumption in million m^3 and the right diagram the per capita consumption in liters/year.

US alone consumed around 15% of the world bottled water in 2011 while about 3/4 of all bottled water was consumed in the ten top countries. Notably Mexico has the highest consumption of bottled water. An interesting aspect is of course to relate the consumption to the general quality of the tap water. The highest consumers do not necessarily have the poorest tap water quality.

It is understandable that people have to buy bottled water where no suitable drinking water is available. Otherwise it is an interesting and disturbing psychological phenomenon. In a country like Sweden people are willing to buy bottled water at a price 3000 times the tap water. Still the tap water quality is mostly superior and is more closely regulated than bottled water. The water price at a gas station in Sweden was three times the price of gasoline. At a European airport I found the water price in the shop to be €10 per liter, while the tap water quality at the same airport is of high quality. According to one study U.S. consumers paid between 240 and 10,000 times more per unit volume for bottled water than for tap water. Typically more than 90% of the cost is not for the water but for bottling, packaging, transport, marketing, retailing and profit. I have found ‘fat free water’ and ‘water that ensures cellular regeneration in your body’.

There are many environmental concerns around bottled water. The huge volume of plastic bottles and all the fossil fuel that is used to manufacture and transport this water around the globe are serious problems. Bottled water is discussed extensively on Internet, but the book Gleick (2010) gives a detailed account of the topic. The energy requirement and the carbon footprint of bottled water, shown in Table 15.2, should motivate a minimum use of bottled water.

Drink tap water whenever it is safe.

21.3 WARM WATER CONSUMPTION

Energy for water heating is a significant component of residential use. Energy consumption on the water demand side is much greater than the energy used for supply, distribution and treatment. In California energy use in the home, for water heating, clothes washing and drying require 14% of California’s electric energy consumption and 31% of its natural gas consumption (DOE, 2006, p. 26; Southwest Hydrology, 2007). The cold and warm water use in a single family in Australia is displayed in Table 21.3.

Table 21.3 Indoor water use in a single family home in Australia.

Water use	Cold water (18°C) liters/household/day	Warm water (60°C) liters/household/day
Taps – kitchen, bathroom	19	20
Showers	41	46
Bath	7	8
Laundry	61	15
Dishwashers	4	1
Toilet	78	0
Total	210	90

Note that the numbers are given for an average household. It is estimated that the per capita consumption is 160 l/day.
Source: adapted from Kenway *et al.* (2008).

The energy Q to heat water is proportional to the temperature change:

$$Q = c \cdot M \cdot \Delta T$$

where Q is the energy (joule, J); c the specific heat (4.186 J/gram · °C) for water; M the mass in g; ΔT the temperature change in °C. Let us calculate the energy to change the volume of 1 m^3 of water from 15°C to 60°C. The mass is 10^6 g, so the required energy is

$$Q = 4.186 \cdot 10^6 \cdot 45 = 188 \cdot 10^6 \text{ J} = 188 \text{ MJ or } 52 \text{ kWh}$$

Note that we neglected the losses during the heating process. The energy requirement is two orders of magnitude more than the energy required to produce 1 m^3 of cold water (compare Tables 15.2, 15.3) and is the key reason why warm water costs a lot. Statistics from various countries show that more than 90% of the water related energy use is spent in the home (DOE, 2001; Reffold *et al.* 2008). Still too little attention is given to this fact.

Significant amounts of warm water can be saved by using showers, washing machines, dishwashers and faucets in a more economical way. So, the lesson is quite simple: reduce the warm water consumption.

Warm water use is the dominating energy use in the water cycle.

Water consumption is usually considered a local issue. However, even if there is plenty of water available the energy needed to heat it generates a carbon footprint, and this has a global impact.

Naturally the choice of energy source for heating is important. If solar heating can be used – a proven technology – huge amounts of carbon emission can be avoided.

The concept of urban metabolism has been used by Steven Kenway (Kenway *et al.* 2011). This is used to get insight in the critical resources of the water cycle and related cycles of energy and nutrients and other materials. These cycles will interact, and therefore there is great challenge to develop integrated solutions.

21.4 OUTDOOR WATER CONSUMPTION

For the outdoor use the irrigation water is of course related to energy use. For our gardens we also use fertilizers, pesticides and herbicides. Fossil fuels were used to manufacture them. The lawnmower often produces more emissions than the car.

Table 21.2 shows that in a typical US home more than 55% of the domestic water consumption is for outdoor use, to keep the grass green. The percentage is even higher in hot inland areas. If the water has to be transported a long way, as in Southern California, the cumulative energy use for the outdoor water consumption is 8.9 kWh/m^3 while it is 2.8 kWh/m^3 in Northern California (DOE, 2006, p. 26; Southwest Hydrology, 2007).

In 2005 NASA analysed satellite images and showed that 32 million acres (130,000 km^2) of lawns were being watered in the US (http://earthobservatory.nasa.gov/Features/Lawn/lawn2.php; retrieved 4 Jan. 2015). This is around three times the area that is irrigated to grow corn or about the same size as Nicaragua or half the size of New Zealand. The U.S. has around 17,000 golf courses and the golf industry is a US$ 76 billion business. Just the lawn care industry itself has a turnover of US$ 25 billion.

There are various methods to save water and energy for irrigation. Sometimes the water price is 'dynamic' depending on availability and consumption. When water is least expensive the user can choose to turn on selected water-consuming appliances such as sprinklers or water-boiler pumps that can run at arbitrary hours. Often individual customers or commercial buildings will turn on sprinklers based on timers. This is an open loop solution and there is no feedback from the real moisture to the delivery of the water. The customer often sets the timer from subjective observations or qualitative information.

The next level of complexity could be considered a feedforward strategy. The idea is that the watering pattern is based on a model that takes the environmental conditions into consideration. The customer will supply information about ground conditions, like the slope of the area, sprinkler placement, sun exposure, and so on. Then the model can be supplied with data from weather satellites so that the watering pattern is adjusted according to the weather. Still the 'final result' of the soil moisture is not measured, so strictly speaking it is not a feedback strategy, but still used. There are commercial systems available based on this principle.

To make the water consumption smarter we would need some kind of feedback, based on real measurements. Agricultural uses are said to be the biggest concerns, with an estimated 15–35% of irrigation withdrawals in excess of sustainable limits, and industrial withdrawals of water are expected to rise 55% by 2025. A lot of crops are irrigated in dry countries. Having a soil sensor that will gauge moisture would provide the basis for feedback control. It is still debatable if a true feedback solution with sensors in the field would be economically feasible, compared to the feedforward model solution mentioned above. Still, it is of significant interest to explore the best solutions from a cost/benefit point of view. Note, that the demand side managements solutions discussed here are all local control solutions in the sense that both the sensors and the actuators are close to the customer.

21.5 WATER REUSE AND RAINWATER HARVESTING

Water reuse and rainwater harvesting are important ways to save scarce water resources in many places in the world.

21.5.1 Water reuse

Significant water, and therefore also energy savings, can be made from the reuse of water where it is used in a second application before being released. We have mentioned reuse of water earlier in the book, as the greywater footprint (Chapter 6), in biofuel production (Chapter 12), in cooling systems in both the power industry (Chapter 13) and in the various process industries (Chapter 14). Using desalination for water reuse is mentioned in Chapter 20.

In Japan where water scarcity is widely recognized it is common to supply not only the drinking water but also recycled greywater and treated effluent wastewater. In Tokyo there are planning rules that require greywater treatment and recycling in all buildings with a floor area larger than 5,000 m^2 (Asano *et al.* 2007).

Greywater reuse and rainwater harvesting can save huge amounts of water and energy.

21.5.2 Rainwater harvesting

Rainwater harvesting can also offer water savings. This is applied all over the world in households, in schools, in agriculture and in urban areas for low quality watering. In industry rainwater harvesting is appreciated for its softness. Roebuck *et al.* (2010) make a financial analysis of rainwater harvesting. Some European data on rainwater harvesting are obtained from the WssTP report on water and energy (WssTP, 2011b).

A number of rainwater harvesting experiences from boh cities and rural areas around the world are reported by UNEP (2015):

- *Berlin, Germany*: In October 1998, rainwater utilization systems were introduced in Berlin as part of a large scale urban re-development, the Daimler-Chrysler Potsdamer Platz in central Berlin. The purpose was to control urban flooding, save city water and create a better micro climate. Rainwater falling on the rooftops (32,000 m^2) of 19 buildings is collected and stored in a 3500 m^3 rainwater basement tank. It is then used for toilet flushing, watering of green areas (including roofs with vegetative cover) and the replenishment of an artificial pond.
- *Singapore*: Almost 86% of Singapore's population lives in high-rise buildings. A light roofing is placed on the roofs to act as catchment. Collected roof water is kept in separate cisterns on the roofs for non-potable uses. A study of an urban residential area of about 742 ha used a model to determine the optimal storage volume of the rooftop cisterns. The study demonstrated an effective saving of 4% of the water used, the volume of which did not have to be pumped from the ground floor. As a result of savings in terms of water, energy costs, and deferred capital, the cost of collected roof water was calculated to be S$ 0.96 against the previous cost of S$ 1.17 per cubic meter.

A rainwater harvesting system is installed in the Changi Airport. Rainfall from the runways and the surrounding green areas is diverted to two impounding reservoirs. One of the reservoirs is designed to balance the flows during the coincident high runoffs and incoming tides, and the other reservoir is used to collect the runoff. The water is used primarily for non-potable functions such fire-fighting drills and toilet flushing. Such collected and treated water accounts for 28 to 33% of the total water used, resulting in savings of approximately S$ 390,000 per annum.

- *Tokyo, Japan*: Rainwater harvesting and utilisation is promoted to mitigate water shortages, control floods, and secure water for emergencies.

The Ryogoku Kokugikan Sumo-wrestling Arena, built in 1985 in Sumida City, utilises rainwater on a large scale. The 8,400 m^2 rooftop of this arena is the catchment surface of the rainwater utilisation system. Collected rainwater is drained into a 1,000 m^3 underground storage tank and used for toilet flushing and air conditioning. Sumida City Hall uses a similar system. Following the example of Kokugikan, many new public facilities have begun to introduce rainwater utilisation systems in Tokyo.

To date, about 750 private and public buildings in Tokyo have introduced rainwater collection and utilisation systems. Rainwater utilisation is now flourishing at both the public and private levels.

21.6 CHAPTER SUMMARY

Water supply is not only the responsibility of the producer. Attitudes and lifestyle of the consumer have a decisive influence how water and energy resources are used. There is a great potential to decrease the cold water use by better equipment and more disciplined behavior. Warm water use has a major influence on the energy balance for the water cycle. The outdoor domestic use is not sustainable in many dry regions. Water reuse and rainwater harvesting offer important possibilities for using the water resources more wisely.

21.7 MORE TO READ

A large number of demonstrations related to water reuse, water consumption and rainwater harvesting available on www.youtube.com (look for ‘water reuse’, ‘water consumption’, ‘rainwater harvesting’ etc.). There is a huge supply and not all of them are good, so be selective.

Among the 49 Specialist Groups within IWA (www.iwahq.org) the two groups on Rainwater harvesting and management (RWMH) and Water reuse are of particular interest here. The book Lazarova *et al.* (2012) is an important contribution to the relationship between water reuse and the water-energy nexus.

PART V

Opportunities

Although I am an engineer I do not believe that the solution of the climate change or water and energy insecurity can be solved by technical innovations only. Of course we all the time have to make operations more efficient and improve the eco-friendliness of products. Among other solutions we have to consider tax regulations, a better way of using subsidies, as well as education, information, motivations for the public.

The decades ahead will present many challenges to humanity. We will need to make use of new sources of energy to power our lives without choking the air. Renewable energy sources such as solar energy, wind power, biomass and geothermal energy are abundant, inexhaustible and widely available. These resources have the capacity to meet the present and future energy demands of the world.

We need to develop several ways of using our planet's never-ending solar insolation flow – for the good and the bad – and an emerging limitation in supply of fresh water, that is, managing energy and water in many ways. A much more complex issue is solar-energy based recycling of CO_2 on industrial and sustainable scales for the mid 2050 decades. Can GHG be a resource?

We will need to be much more frugal and think more in terms of residual energy recovery and of water recycling and reuse. Climate change and a growing population force us. We must recycle, recover and reuse on a scale not yet imagined, and to balance the convenience of consumption with the wisdom of conservation. Perhaps most importantly, we will need to develop ways of doing much, much more with our planet's limited supply of fresh water.

All of us – all the seven billions – are one family that lives on the same planet. This not only requires a bold leadership but also an insight that we have to share our limited resources. There is no excuse for public officials not making clean water for everybody a top priority. The world can afford it. It is a matter of our priorities and attitudes. Water can no longer be ignored – nowhere.

Water and energy illiteracy are problems that have to be addressed everywhere. We see and hear political leaders that still ignore or dispute our role in the climate change. We simply have to inform, educate, and hopefully change our habits and attitudes.

In the four first parts of the book we have described many of the problems and challenges that become visible when the couplings between water, energy, food and land use get apparent. In this final part we will consider some possibilities for a more sustainable future.

22 Possibilities and solutions

> *There is a sufficiency in the world for man's need but not for man's greed.*
>
> Mohandas Gandhi

In the four previous parts of the book we have illustrated the close relationship between water, energy, food and land use.

- The nexus (Part I):
  - Water cannot be used and water supply and treatment cannot be operated without energy;
  - Energy operations require water; for extraction, refining, electric power generation;
  - We have seen an increasing number of competitions and conflicts between water and energy;
  - With increasing water scarcity in many parts of the world it becomes crucial that water and energy are planned and considered together – integrated planning;
  - Energy production and generation causes pollution of both water and air;
- Water vs climate change – population – food – land use (Part II)
  - Climate change already has a profound influence in water resources as well as energy production. The unsustainable use of fossil fuels has to be changed, but the actions so far are too small and too late (Chapter 4);
  - The population increase is maybe the largest challenge for water, energy and food availability. We should be able to support the whole world population. The most problematic issue is to achieve a fair distribution of our resources (Chapter 5);
  - Energy, food and land use have become increasingly in competition. Using agricultural land to produce food that is converted into biofuel is controversial (Chapter 6);
  - Climate change, overuse of groundwater and misuse of our water resources have created increasing water scarcity, conflicts and suffering (Chapter 7).
  - The value of water is seldom reflected in its price. Water is (and should be) a human right. But it is not a human right to waste water in an arid region and it is not a human right to pollute it. The real value of water has to match the price we pay for it (Chapter 8).
- Water for energy (Part III):
  - Our energy consumption has increased dramatically and will continue to grow. This will have profound consequences for the world's water resources (Chapter 9);

  - Hydropower can be sustainable and a renewable source of electrical energy. However, poorly designed dams may be a serious threat to water resources. Integrated planning, considering many aspects of dam building, should be the norm (Chapter 10);
  - Fossil fuel burning is the exceptional threat to our climate. Oil, gas and coal extraction also have far-reaching consequences for water availability as well as for water quality (Chapter 11);
  - The use of biofuels is controversial. The first generation of biofuels not only competes with food production but often has a low energy yield. The water use is sometimes unacceptable. The second generation biofuels, based on cellulose, can prevent the competition with food production (Chapter 12);
  - Cooling thermal power plants creates a major challenge in water scarce areas. The water need for cooling has already been a limiting factor for electric power generation in Europe, US, China, and South Africa (Chapter 13);
  - Industrial use of water has to increasingly look at water saving procedures, water recirculation and water re-use (Chapter 14).
- Energy for water (part IV)
  - All water operations depend on energy. The challenge is not only to save electrical energy but to utilize the inherent energy in wastewater (Chapter 15);
  - Pumping is a major energy consumer in water operation. The potential for more efficient operations is apparent (Chapter 16);
  - Aeration is a key operation in biological wastewater treatment. It can be made more energy efficient by better control and operation (Chapter 17);
  - Biogas production has a lot of potential but is usually utilized far from its full capacity (Chapter 18);
  - Heat content in water and wastewater is a source of energy that can be more exploited (Chapter 19);
  - Using desalination for fresh water supply is increasingly used to overcome serious water scarcity problems, but the energy price is high (Chapter 20);
  - Both energy and water systems have traditionally been supply-oriented. It is time to involve the customer to save resources and to make the system demand-oriented. A user that is aware of the potential of savings is a necessary partner in the attempts to meet the scarcity challenges (Chapter 21).

We need to think differently, radically differently, to seriously tackle the problems of climate change, water scarcity and energy use. I have come to the gloomy conclusion that the fossil fuel industry in particular does not possess the incentives (see Chapter 11.9) to prevent climate change and to reduce the pollution of the atmosphere. Any far-reaching change will depend on strong political leadership. However, for political leaders to get the courage to make radical decisions about climate change, we – the grassroots – have to support them.

The key word is reduce:

- reduce the amount of fuel we use (car, air travel, heating, cooling, and so on);
- reduce the amount of misused electrical energy;
- reduce our water – in particular warm water – consumption in the high-income world;
- reduce the animal products that we consume (meat, dairy, eggs, leather, and so on).

It is less expensive to save one MWh ('Negawatt'-hour) than to produce one MWh. Reduction is closely related to efficiency. Energy and water saving equipment as well as monitoring, control and automation are tools to obtain better operation, both at the production side and on the demand side.

There are so many opportunities, such as:

- Possible future technologies that is more energy and water efficient (Section 22.1),
- Renewable energy sources (22.2),
- Attitudes and life style (22.3),
- A number of possible actions (22.4).

Some final reflections are made in 22.5.

22.1 POSSIBLE TECHNICAL SOLUTIONS

> *It's not that I'm so smart; it's just that I stay with problems longer.*
>
> Albert Einstein

The increasingly integrated world of shared resources and trade requires a new paradigm of operation. This applies doubly to water and especially water for energy production and conversion. Gone are the days of each country or region looking out only for itself. Operations are now interregional and international.

Some encouraging developments take place in various parts of the world. Many national and international organisations make a fantastic work to improve the world. Just one example: in China a program called 'Save a Barrel of Water' started in 2005 and covers 24 cities with a total of 1.3 million participants (China Daily, 31 October, 2011). The program is estimated to have saved 430,000 m^3 of water. It does not eliminate the water scarcity but is a great step forward. At Tsinghua University in Beijing there is a Student Green Association that has participated in a nationwide water-saving competition. Zhou Hui, president of Student Green Association of the university, a senior student of the School of Environment, won the chance to join in the torch relay in the London Olympic Games 2012. She was the first torchbearer that was selected in China mainland.

22.1.1 Water

Many existing and new technologies show promise for making water more available and its use more efficient (such as recirculating as opposed to once-through systems, dry cooling, desalination, recycling and cleaning rather than wasting water from oil extraction and coal mining). However, to accelerate the entry of these technologies and their benefits into common usage, policymakers in both businesses and governments must carefully examine policy measures and conditions that will achieve this. We have discussed the importance of efficient water use:

- in agriculture (Chapter 6);
- in primary energy extraction (Chapters 11, 12);
- in cooling systems (Chapters 13, 14);

- in water distribution, to minimize leakages (Chapters 8, 16);
- in more efficient pumping systems (Chapter 16);
- at home, indoor and outdoor (Chapter 21);

Pricing of water today has very little correlation to the value of water. The tariff could be made a better driving force for a responsible use of water. This should engage economists and planners (Chapter 8).

22.1.2 Energy consumption

The global energy use will rise as a result of rising standards of living in the developing countries and of the increasing population (Chapter 9). However, the progress made by more efficient energy use is offset by continuously increasing needs. This is true for all kinds of energy sources.

Using energy more efficiently will probably be the fastest and cheapest way to emission reduction. There are tremendous differences in energy efficiency across the world. This shows that a lot can be achieved already with what our current technology can achieve. According to IEA (2010) the most efficient economies (like Japan) generate almost 16 times more money, measured in GDP, using the same amount of energy than the least efficient (Russia). The key advantages of existing energy-efficient technologies are that they are tried and tested, and investment payback times are short.

Electric drive systems

Electric motors are the workhorses of industry. It is estimated that motors convert about 2/3 of all the electric energy used by industry into mechanical energy. Since industry uses about 42% of the global electrical power there are huge opportunities to save energy, simply by improving the operation of motors, for example by variable speed drives instead of throttle-valve constant-speed systems (Chapter 16). Some cases of significant savings are listed (information from www.abb.com/motors&drives) here:

- A German city waterworks upgraded its clean water pumping station control by installing a variable speed drive. The estimated energy savings were about 50% or about 740 MWh/year. Another benefit was a constant water pressure.
- In a river-water pumping station pump with rated power 1500 kW was used. The load is variable and a throttled constant speed pump is inefficient. A variable speed pump could save 32% energy or 2400 MWh/year. The reductions in CO_2 emissions are significant and the payback period is less than 1 year.
- Residual energy recovery is an area where development opportunities exist. For example, in the steel industry in Sweden some 2.8 TWh of such energy was used already in 2007 for electrical production and external district heating. In addition, process gases equivalent to 4.6 TWh were used internally in different processes (www.jernkontoret.se).
- Energy harvesting is discussed seriously (Bhaskaran *et al.* 2013). People have been looking for decades for ways to harvest energy from natural sources and climate change has triggered a lot of activities in this respect. Residual energy recovery may be developed for cars. Since water is an excellent cooling substance (as discussed in Chapter 13) it is also used for engine cooling in most cars. Is it possible to convert the wasted heat into electricity?

- District heating (see further Chapter 19) can be further expanded using residual heat recovery from industries.
- It is important to have tax and certificate rules for electricity production that would make energy recovery profitable when there is no market for heat recovery.
- At a wastewater pumping station the maximum flow rate is 750 m^3/h and the average flow rate 400 m^3/h. The pump is operated for 8000 hours/year. The motor output is 70 kW. Three control methods were compared. Throttling required 44 kW, on-off control 32 kW and variable speed control 23 kW. The payback period for variable speed control was estimated to 6 months. The control also contributed to better operation of the treatment process (compare Chapters 16 and 17).
- Cooling water for thermal power plants is not only a matter of water volumes but also of energy. A European power plant considered changing its 1.45 MW feedwater pump to variable speed. The comparison showed that within the speed range needed the variable speed drive needed 150 kW less power. The yearly energy savings were estimated to 1200 MWh and several operational advantages were obtained, plus the reduction of GHG emissions.

Energy intensive industries

All economic sectors use large quantities of electricity. For some industrial sectors the need for electricity is staggering: the generation of low-cost bulk power quantities is the reason why large electricity consumers are often located in proximity of large power plants. Many industrial processes simply use the energy as a necessary raw material of a product and do that in an efficient way. Other energy users may have designed the systems for cheap bulk electrical energy and now need to re-think. The search for new ways to produce electricity must go together with the search of new ways to convert and consume it.

The rational use of energy and efficiency is now officially promoted in many countries. Important opportunities are for:

- Saving energy by hot and cold water recycling in industry (Chapter 14);
- Using variable speed motor drives (Chapter 16);
- Maximizing pump efficiency for the most commonly operated flow rates (Chapter 16);
- Controlling dissolved oxygen in wastewater treatment (Chapter 17);
- Allowing variable pressure in water distribution (Chapter 16.3) and in air supply systems in activated sludge plants (Chapter 17.2);
- Optimizing the operation of biogas production (Chapter 18);
- Using the heat content of groundwater, surface water and wastewater for heating and cooling, both in industry and in residential areas (Chapter 19).

Energy at home

Households are large electricity users. Domestic appliances such as refrigerators, dishwashers, ovens, lamps, and other common household devices use a large portion of the generated energy in high income countries. Furthermore, residential appliances such as space cooling and heating consume plentiful electric power. The differences between countries are very large and the contrast to some developing countries is disturbing and embarrassing. Still, household electricity consumption in the high-income part of the world is projected to increase in the coming years because of the wider diffusion of IT, communication, and other family entertainment devices, together with the decline in the average number of people per household in developed countries. More appliances are necessary, because they are shared by less people.

By reducing hot water consumption at certain times the electric power peak can be reduced, thus reducing both the consumer energy bill and the marginal power production bill. Water saving shower heads are widely available. The use of washing machines and dishwashers can be postponed to off-peak hours. Simple solutions offer timers of the machines indicating when the machine should be completed. More elaborate solutions will connect the power (and water!) price to operate the machines at the best time.

Heating, ventilation and air conditioning (HVAC) require a lot of energy. Every single degree that we can let the temperature decrease in the cold season and increase in the warm season will have a major impact on the energy consumption. There are already available information systems to monitor the energy flow for HVAC. The payback time of such equipment is most often quite short and will shorten when the information systems become more wide-spread and the energy prices higher. In IPCC (2014a), Chapter 10, we are reminded that the global demand for residential air conditioning in summer will increase rapidly in the next decades and the fastest growth will take place in the developing countries. It is estimated that 75% of the increase from about 300 TWh in 2000 to about 4,000 TWh in 2050 is due to an increasing income in emerging market countries, while 25% is due to climate change.

Behavioral changes as well as pricing can save energy. Often we have to become aware of our habits and simply apply common sense to save water and energy.

Energy in buildings

There is a high agreement in the IPCC work (IPCC, 2014b, page 26) that lifestyle, culture and behavior significantly influence energy consumption in buildings. It has been shown that the energy use to provide similar building-related energy service in buildings differ a factor of 3 to 5 between different cases. In the rich part of the world scenarios indicate that lifestyle and behavioral changes could reduce energy demand by up to 20% in the short term and by up to 50% of present levels by 2050. In the low-income countries the integration of traditional lifestyles into building practices and architecture could provide high levels of energy services with much lower energy inputs than baseline (IPCC, 2014b, Chapter 9). There are other positive outcomes of mitigation efforts on top of energy efficiency, for example improvements in energy security, cleaner wood-burning cookstoves that will have health implications and environmental consequences. Also workplace productivity will be influenced by better energy efficiency in buildings.

The importance of improving buildings codes for more efficient housing and buildings is emphasized in IEA (2012), Chapter 11. Energy management systems can offer a lot of possibilities. Architectural improvements are important, such as reduction of per-capita floor space requirements through better layout design.

Energy storage

Among renewable energy resources, solar energy is by far the largest exploitable resource, providing more energy in 1 hour to the earth than all of the energy consumed by humans in an entire year.

Energy storage is becoming increasingly important when more wind and solar energy sources are used in the power grids. The wind generators only deliver when the wind blows and the solar devices do not produce in the night. There is a large development work going on to find out better energy storage facilities. Water in hydropower is a classical storage for electrical power. Other means, such as batteries and super-capacitors, are also emerging. Storage of thermal power is a proven technology (Chapter 19.1). A particularly attractive approach is to store solar-converted energy in the form of chemical bonds, that is, in a photosynthetic process at a year-round average efficiency significantly higher than current plants or algae, to reduce land-area requirements (Lewis-Nocera, 2006). Scientific challenges involved with this process include schemes to capture and convert solar energy and then store the energy in the form of chemical bonds, producing oxygen from water and a reduced fuel such as hydrogen, methane, methanol, or other hydrocarbon species.

It would be most interesting (and realistic) to see wave power or wind power in connection with seawater desalination (Chapter 20.8). Whenever there is a surplus of wave or wind energy it can be stored as freshwater. The excess energy does not necessarily need to be delivered to the grid system. In this way all available energy can be used without any carbon footprint.

Solar heating is getting more and more common. For example, large office buildings are equipped with a special kind of glass facades. The air between the glass surfaces is heated by the sun. Via an air/water heat exchanger the heat is transferred to water and distributed in the building.

Communication between water and energy professionals

Integrated solutions have to be found in the planning and operation of water and energy systems. At various places in the world there are ‘water dialogues’ and ‘energy dialogues’ taking place. From these dialogues one aspect should be mentioned. The water and wastewater industry needs to speak with one voice, having one common message. However, different parts of the industry do not always speak the same language, since water, wastewater, groundwater and stormwater have shaped too many fractions of the water industry. There are, however, excellent role models of integration; Waternet in Amsterdam is responsible for all water operations and Mälarenergi in Sweden handles both water and energy. The industry has a splendid story to tell, but we have to get together – engineers, regulators, politicians, economists, and other stake holders – to deliver and listen to the key messages.

Water and energy people have to meet, to understand their respective challenges, and together find solutions that are acceptable, economic and sustainable. Scientific water papers should be presented at power system conferences as naturally as energy papers are presented at water conferences.

22.1.3 Energy production

There are many opportunities to make current energy production systems more water efficient.

- *Fossil fuel extraction*: Fossil fuel extraction and production can be made more water efficient. The water quantity used for conventional oil and natural gas extraction, hydraulic fracturing, tar sand extraction and coal extraction can be much more reduced by increasing the reuse and recirculation of produced water (Chapter 11). Furthermore, pollution of water means consumption of water. It should be self-evident that the polluter should pay. Why this is not done is a mystery and a shame.

- *Thermoelectric plant cooling*: the requirement of water for cooling can be reduced. This will include innovative cooling technologies, non-traditional water supplies (like municipal wastewater or brackish groundwater) as well as water reuse (Chapter 13).
- *Biofuels*: the water use for biofuels was discussed in Chapter 12. To use irrigation for biofuel is generally a very expensive way of producing energy. Water efficient conversion of biomass into biofuels should be further emphasized.
- Renewable energy sources like wind and solar PV are often intermittent. This requires flexible grid operations, and the development of smart power grids is part of the overall goal to save energy and to increase reliability and resilience. By increasing the renewables water will be saved (see 22.2).
- Demand side management can be realized both directly (by automation and technical devices) and indirectly (by customer behavior). Part of it depends on energy/water smart appliances. Part of it depends on the customer behavior. Here one important part is measurement information. If the customer becomes aware of the consumption of energy and water it will probably have an influence on the consumption.

22.2 RENEWABLE ENERGY

Renewable energy like wind and solar PV do not require any water for their operation, unlike fossil fuel-based and nuclear power plants (Chapter 13), but sometimes require small amounts of water for cleaning purposes. If the significant use of water during the extraction of fossil fuels and uranium is considered (Chapter 11), then the difference in water use is even greater. Wind and solar PV avoid any thermal pollution and contamination that may be the result of cooling water discharges from thermal power plants. Obviously, wind and solar PV will contribute to a low-carbon energy future.

The cost of energy generated from these renewable resources is significantly coming down while the cost of fossil fuel produced energy is in an increasing mode. Over the last two decades solar and wind energy systems have experienced rapid growth. This is being supported by several factors such as declining capital cost; declining cost of electricity generated and continued improvement in performance characteristics of these systems.

The fossil fuel development is controlled by enormous economic forces, as noted in the introduction of Chapter 11. More than half the world population live in urban areas. The population density requires high power density of energy supply, both of electricity and of fuels. It is a huge challenge to meet these demands quickly with wind and solar PV, due to their intermittent nature. Energy storage is a key factor. However, the potential is enormous, but we have to discover it. The problem is that the whole civilization has been built on fossil fuels and the transition will take time, not only because of technology but to a large extent due to habits and attitudes.

IEA (2012) devote a whole chapter 7 of the World Energy Outlook on renewables, primarily wind and solar PV. The development of renewable energy is considered carefully by all the large energy corporations. It is quite natural that each one of them has their specific perspective (and desire). IEA predicts that wind and solar power will account for almost one-third of total electricity output in 2035 (IEA, 2012, Table 7.2). Solar grows more rapidly than any other renewable technology, from 32 TWh in 2010 to 846 TWh in 2035, a factor of 26 in energy generation. Wind is expected to increase its output from 342 TWh in 2010 to 2681 TWh in 2035, a factor of almost 8.

It is estimated that the global increase in solar PV capacity until 2035 will be almost as big as that of hydropower and more than 2.5 times as large as the net increase in nuclear capacity. However, energy output from the solar PV is expected to be half of that of nuclear due to the variability of the sunshine (IEA, 2012, Chapter 6). ExxonMobil (2015) expects that the solar capacity to grow 20 times from 2010 to 2040. More than half of today's installed solar capacity is non-utility scale distributed, such as rooftop solar for residential and commercial applications. It is expected that distributed generation via solar PV will continue to be the dominating share of the solar market. Wind capacity will expand almost five times in the period 2010 to 2040.

22.2.1 Solar PV

The resource potential for solar PV is enormous. The global solar PV capacity increased from 1 GW in 2000 to 67 GW in 2011 (IEA, 2012) and in 2012 alone the capacity increased by 30 GW. In 2013 another 40 GW were installed, and the total installed solar PV capacity reached 137 GW in 2013. IEA (2012) predicts in the New Policies Scenario that installed solar PV capacity will increase to just over 600 GW in 2035. The annual PV contribution to electricity demand has exceeded 1% in 17 countries. Italy is at the top with 7.6% and Greece and Germany above 6%. The overall European PV contribution amounted to around 3% of Europe's electricity demand while PV contribution to the global electricity demand reached 0.87% in 2013. Australia has also passed the 2% mark and Japan 1.5%.

An important advantage of solar PV is its modularity, meaning that solar panels can be installed for applications ranging from a single house to large utility-scale arrays. Distributed – or onsite – solar generation is becoming increasingly attractive as the cost of PV cells comes down. Solar PV in buildings can reduce the needs for transmission and distribution capacity in the grid. Obviously, the intermittent production will require sufficient distribution capacity to balance the variations, but the average distribution capacity to the customer can be reduced. This is of course site specific; for example, if the solar PV is used to supply air conditioning, then there is a high correlation between solar input and energy need.

Another aspect of power plant construction that is seldom mentioned, the availability of skilled workers assembling the plant. This was recently demonstrated for me in Kenya. A solar PV installation of about 1 MW could be readily installed in a remote area with a minimum of specialist workers involved. Workers familiar with road building could plan for the solar PV foundations. The percentage broken solar panels was lower than normal. No special cranes or helicopters were needed for the assembly (as for wind power) and the installation was completed on time.

22.2.2 Solar PV pricing

The cost for solar PV has been reduced dramatically in recent years. Solar PV is quickly becoming more competitive. The cost of solar PV panels dropped 65% from the first quarter of 2010 to the last quarter of 2012. The price decreases were the result of a combination of decreasing component costs, reduced labour costs and decreasing margins as a result of growing competition and manufacturing capacity, especially in China. There has been an overcapacity of the industry. Trade tensions have arisen between the US, Europe and China, and the US introduced import tariffs in 2012 on solar panels from China. An overview of the solar PV pricing development in the US during the last few years is given by the US Department of Energy (Sunshot, 2014). Some key facts are summarized in Table 22.1.

Table 22.1 Reported pricing for PV system installations.

	Residential and small commercial (≤10 kW)	Large commercial (>100 kW)	Utility-scale (≥5 MW, ground-mounted)
	US$/W (median)		
PV system installations completed in 2013	4.69	3.89	3.00
System prices quoted in Q4 2013, expected to be installed in 2014	3.29	2.54	1.80

Source: Sunshot (2014).

Reported system prices of residential and commercial PV systems declined 6%–7% per year, on average, from 1998–2013, and by 12%–15% from 2012–2013, depending on system size.

The system prices of both utility-scale and distributed systems are expected to decrease in the near future. Distributed systems are expected to reach between 1.5 and 3.0 US$/W by 2016, while utility scale systems are estimated to cost between 1.30–1.95 US$/W by 2016. Apparently the price reductions have been larger than were expected a few years ago. The 2020 price projections in 2014 are more than 50% below what modeled pricing showed in 2010.

22.2.3 Wind power

IEA (2012) predicts that wind power will generate twice as much electricity as coal in 2035. It is expected that wind power, especially on-shore wind, will become fully cost-competitive on a pure commercial basis compared to other energy generation technologies within the next few years, at least in Europe. In the US the low gas prices and the absence of any CO_2 price makes competition tougher. In the New Policies Scenario IEA (2012) predicts that wind power will increase its share in total electricity generation from 1.6% to 7.3% in 2035. In Europe the wind power share was less than 5% in 2010 but will grow to almost 20% in 2035. The units are becoming larger: in early 2015 the largest wind power unit (in the sea outside UK) has a generating capacity of 7 MW and a turbine diameter of 171 m. Table 22.2 summarizes expected wind power developments in some regions over the next 20 years.

Denmark has been a pioneering country for wind power. During the first half of 2014 41% of the electrical energy came from wind. At certain times 100% of all electricity was delivered from the wind power systems (www.Energinet.dk). Danish wind power records are also world records, as no other country has a larger wind power capacity in proportion to power consumption, according to Energinet.dk. Denmark's grid is flexible because of the country's combined heat and power (CHP) plants and grid connections to other countries, which helps the operator to balance supply and demand. In January 2014 wind power output set a new monthly record, providing 61.7% of Denmark's electricity consumption. The new challenge is now to balance the required heat and electricity production in the CHP plants with the wind power electricity production.

Table 22.2 Expected wind power capacity in some regions in the IEA New Policies Scenario (GW)

	Wind onshore		Wind offshore		Wind total	
	2011	2035	2011	2035	2011	2035
US	47	143	0	18	47	161
Europe	91	231	4	72	95	304
Japan	3	16	0	9	3	25
China	62	280	0	46	62	326
India	16	93	0	5	16	97
World	235	923	4	175	238	1098

Source: IEA (2012), Table 7.5.

22.2.4 Geoengineering

It is well recognized that it is necessary to change people's habits and attitudes, but this is a slow process. The danger of climate change requires immediate action. This has encouraged a lot of development of more or less realistic methods to deliberately reduce the impact of anthropogenic climate change, either by actively removing greenhouse gases from the atmosphere or by decreasing the sunlight absorbed at the Earth's surface. This could involve various means of injecting particles into the atmosphere in order to reflect more sunlight back to space. This is called Solar Radiation Management, assuming that we really can 'manage' the sunlight. The most science fiction like proposal is space mirrors. Another is 'cloud brightening': spraying seawater into the sky (from boats or from towers on shore) to create more cloud cover (Lenton- Vaughan, 2013).

Still another approach is to spray sulfate aerosols into the stratosphere via special airplanes or via helium balloons. The last suggestion is often referred to as the 'Pinatubo Option' after the 1991 eruption of Mount Pinatubo in the Philippines. Most volcanic eruptions send ash and gases into the lower atmosphere, where sulfuric acid droplets are formed that simply fall down to earth or can be sent even to the stratosphere. The first question is of course: does it work? The second is: who can decide about dimming the sunshine globally? But the critical issue is that it does nothing to change the fundamental cause of climate change. Even if it would dampen the heat somewhat the oceans would still have to absorb atmospheric carbon that will cause further acidification. Even worse: it is well documented that the eruption of Mount Pinatubo also caused significant losses of rainfall. Climate computer models have been simulated, where not only greenhouse gases but also sulfur has been added to the atmosphere. Some of the results are sufficiently severe to force everybody to re-consider the whole idea. Asian and African summer monsoons would be disrupted causing a deadly risk for a large portion of the world population.

The general impression is that all geoengineering methods look like quick fixes developed in high-income countries so that we do not have to change our behavior. How could we guarantee that the poor income countries would not be hurt? Remember, these methods cannot be evaluated in small scale. They have to be tried, untested, in full scale. Many leaders have believed that they could control Nature. How many rivers are dry at the outlet? Remember the Aral Sea! Do not forget Deepwater Horizon in the Mexican Gulf! Learn from the Niger Delta!

22.2.5 Power density – land area requirement for electricity generation

One element of key interest for energy systems is the 'energy density' of various energy types. Fuels high in energy content use less space and are often the easiest to transport for various uses. This helps explain why gasoline is prevalent as a transportation fuel and why people in high-rise buildings do not rely on wood for heating and cooking. Power density is a measure of how much electricity can be generated for a given area of land. Then it should include the land needed for coal mining and gas production as well as the actual footprint of nuclear power plant or a wind or solar farm. One concern regarding large-scale deployment of solar PV and wind energy has been their potentially significant land use. For that reason we will compare the power density, expressed in MW/km^2 land use.

It is not trivial to give a unique definition of the required area. Three general considerations are used to evaluate land use impacts: (1) the area impacted, (2) the duration of the impact, and (3) the quality of the impact. The quality of the impact (also called the 'damage function') evaluates the initial state of the land impacted and the final state across a variety of factors, including soil quality and overall ecosystem quality (Denholm *et al.* 2009; Ong *et al.* 2013). It has to be recognized that the quality and duration of the impact must be evaluated on a case-by-case basis.

We will here discuss areas for four electric power sources that are considered to be part of renewables:

- *Hydropower*: the area requirement of the reservoir. Here we calculate as if the only purpose of the reservoir is for hydropower. Often multiple use of the reservoir will motivate the use of the dam, even if the power density will be low.
- *Biofuel*: the agricultural area required to grow the biomass that will be converted to biofuel. Here we will calculate the energy generation in one year and only one harvest in a year.

For wind and solar PV we consider two types of areas, total area and direct impact area (Denholm *et al.* 2009; Ong *et al.* 2013). The first one corresponds to all land enclosed by the site boundary. The direct impact area comprises land directly by wind turbines or solar arrays, access roads, substations, service buildings and other infrastructure. Naturally the direct impact area is a part of the total area.

- *Wind*: for our evaluation we use the total area, recognizing that this will give a less favourable energy density. Still the energy density for wind power is competitive to other energy sources. Furthermore, the area between the wind towers can often be used for agriculture or forest.
- *Solar PV*: the total area is used for the evaluation. Note that a large part of solar PV panels can be mounted as rooftops and does not compete with other uses of the area.

Hydropower: In Chapter 10 we discussed the reservoir area for a number of hydropower plants. For the hydropower plants presented in Table 10.2 the power density varies between 0.14 and 380 MW/km^2. Neglecting the apparent outlier San Carlos in Colombia the highest density is above 10 MW/km^2. Adding further information from Table 10.3 the maximum density is found in the Three Gorges reservoir of 17 MW/km^2, and the low extreme Balbina has the capacity 0.08 MW/km^2. For our comparison we use the range from about 0.1 to 17 MW/km^2.

Biofuel: the production of biofuel from corn (maize) and sugarcane is described in Davis *et al.* (2014). According to Davis (page 73) 1 hectare of corn generates around 2000 liters of bioethanol. This is calculated as a global average. The yields vary widely across the world, from total biomass yield less than 1 ton to 28 tons/ha. The 2000 liters of ethanol has an energy content of 24 MJ/l (Appendix 2), resulting in 48 GJ/ha or 13 MWh/ha = 1.3 GWh/km^2 per year. The yield of bioethanol from sugarcane is much higher than from corn. The global average is 5,800 liters/ha of bioethanol (Davis *et al.* 2014, page 76), which will have an energy output of 140 GJ/ha or 3.9 GWh/km^2 per year. Note, that we have not calculated the efficiency of transforming bioethanol to electric power. Therefore the true electrical energy content is much less.

Wind: Denholm *et al.* (2009) have estimated the land use of 161 wind power projects in the US. Considering only 125 of the 161 projects, representing 80% of the evaluated capacity, a total area requirement is found to be in the range of 2–10 MW/km^2. Excluding the outliers the power density was anywhere between 1 and 11.2 MW/km^2. Denholm *et al.* also report previous theoretical calculations of 5 MW/km^2. Some estimates have assumed a fixed array spacing, such as 5 rotor diameters by 10 rotor diameters (a 5D by 10D array). For modern wind turbines such arrays would yield 5–8 MW/km^2.

The impact of the wind velocity is critical, since the wind power increases with the wind velocity v as v^3. This means that even a small reduction in wind velocity will have a significant influence on the ability to generate power. A site with an average wind speed of 5 m/s has only half the energy available as a site with the wind speed 6.3 m/s.

The Horns Rev off shore wind farm of 160 MW is located in the eastern North Sea, about 20–30 km outside the westernmost point of Denmark. The wind farm was commissioned in 2002. The area defined for Horns Rev was 20 km^2 for the 80 turbines, generating 160 MW. Thus the power density is 8 MW/km^2 (www.power-technology.com/projects/hornsreefwind).

Solar PV: The land use for solar PV has been analyzed by Ong *et al.* (2013). The authors have analyzed a majority of the solar plants installed or under construction in the US in the 3rd quarter of 2012. For the majority of the solar PV plants the power density is between 28 and 33 MW/km^2. The direct land use requirements for small (1–20 MW) and large (>20 MW) installations range from 20 to 110 MW/km^2 with a capacity weighted average of 36 MW/km^2. Fixed tilt systems use 13% less land than 1-axis tracking systems on a capacity basis. However, considering the total energy generation the fixed tilt system uses 15% more land. The difference is explained by the increased generation resulting from tracking technologies. A 1-axis tracking system can increase the solar PV average energy generation by 12%–25% compared to the fixed tilt systems and 2-axis tracking systems can increase PV generation by 30–45%. The numbers given cannot represent solar PV in general, but can give a reasonable estimate of the order of magnitude.

In order to calculate the total energy generated from a specific source we need to take the capacity factor into consideration. The variability of wind and sunshine is the reason that the wind power or solar PV cannot be used at full capacity all time. Also for hydropower the capacity is hardly ever at its maximum. The net *capacity factor* of a power plant is defined as the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at maximum power output. For hydroelectricity, the global average is 44% (Kumar *et al.* 2011, p 446) and the range is 10%–99% depending on design and local conditions. The averages of the continents vary from 32% (Australia, Oceania) to 54% (Latin America). Wind capacity factors range from 20 to 40% so the power density has to be reduced accordingly. For solar the capacity factor depends on the latitude and weather pattern. Some typical values are 9% (UK), 13–15% (Massachusetts, US), 19% (Arizona, US), 18% (Portugal). Compare the discussion of capacity factors in Chapter 10.1.

The annual energy output from 1 km^2 of area for different types of renewable energy sources is summarized in Table 22.3. The capacity factors are chosen to be typical for the kind of energy source, but naturally the values are site specific. This is true for water availability in hydropower systems, yield of biomass production, wind speed and solar intensity. For hydropower we have chosen an optimistic value of 60%, for wind 30% and for solar PV 20%. The table is aimed to give an order of magnitude of the energy potential related to the area requirement.

Table 22.3 Annual energy output from a given 1 km^2 area for different renewable energy sources.

	Hydropower	Biofuel[1]	Wind	Solar PV
Power density MW/km^2	0.1–17	n.a.	5–8	20–110
Capacity factor	0.6	n.a.	0.3	0.2
Annual energy output GWh/km^2	0.5–90	1.3–3.9	13–21	35–190

[1] Note that this shows the energy content, not the electrical power output.

- It is quite apparent that wind and solar PV are superior not only from a climate point of view but also from an area requirement point of view. Still the potential for solar may be even larger. For example in Kenya (Kenya Energy Regulatory Commission) the average daily insolation is of the order 4–6 kWh/m^2 which corresponds to 1,800 GWh/km^2.
- Hydropower very often has an extremely low production of power per flooded area. Then the reservoir can only be motivated from a multiple use point of view.
- Biofuel is an expensive way to produce energy. The required area is large. Furthermore, a lot of fossil energy will be used to produce the biomass and biofuel. On top of that there are significant water quality issues related to fertilizers.
- It is recognized that many people resist wind power with the argument ‘not in my backyard’ (NIMBY). Here we just note the area requirement and find that the area on-shore can be used also for other purposes. Off-shore wind will of course have environmental impact but the area seldom competes with other uses.
- Solar PV can have a superior area requirement. So far a lot of expansion of solar PV has been distributed as small units in residential and industrial areas. Using rooftops means that the solar PV does not compete with other uses.

It is obvious that wind and solar PV can be increasingly competitive. The comparisons above have not taken the cost into consideration. The subsidies have to be taken into account. To foster the deployment of renewable energy, governments use subsidies to lower the cost of renewables or raise their revenues, helping them compete with fossil fuel technologies (we should remember the large subsidies to fossil fuels, Chapter 11). The justification for subsidies for the wind and solar is that imperfections in the market fail to factor in externalities (fossil fuels do not pay for the pollution of the atmosphere) or deny nascent technologies the opportunity to mature without support. The ultimate goal is to help renewable energy technologies to achieve sufficient cost reductions to enable them to compete on their own merits with conventional technologies. At that point, any support should, accordingly, cease to be awarded to additional capacity.

In Chapter 20 we described how wind power can supply power for desalination plants. We can use the sun much more than only for solar PV. Solar thermal systems are proven technologies and affordable for most people. To heat water via solar thermal panels would save huge amounts of energy, adding to the renewable technology that should replace the fossil fuel production.

22.3 ATTITUDES AND LIFE STYLES

> *The greatest discovery of any generation is that human beings can alter their lives by altering the attitudes of their minds.*
>
> Albert Schweitzer.

Most people in high-income countries have a feeling for the price of energy. As remarked in Chapter 8.2 the awareness of the water price, however, is almost nonexistent. Drinking water is undervalued as a resource and wastewater is undervalued as a service. It is difficult to convince the public that there is a water crisis or a coming water crisis when you can turn on the tap in a city located in a half desert and then take a 15 minute shower without any prohibitive cost.

> *Education at all levels is crucial.*

We have to have the drive and passion as well as the entrepreneurship to sending the message. We must make any endeavour to help politicians to explain the issues for the public. Education is so important that people should understand that even if the water and energy delivery is hidden under ground one still needs to pay for it. People need to be aware of what we are spending and why. We have to be good to explain what and why we are doing things. If the industry is like the infrastructure – out of sight – then the public has difficulties to appreciate what the industry can do.

We make the issue apparent for people and learn from experiences in many countries. Even in a water-rich country energy can be saved by saving water. The climate change is sufficiently far-reaching to be taken seriously.

22.4 POSSIBLE ACTIONS

> *Plans are only good intentions unless they immediately degenerate into hard work.*
>
> Peter Drucker (1909–2005).

So, what would we do? This book has tried to enhance the awareness and participation of stakeholders – the decision makers, the investors, the water and energy producers, the water and power engineers, the large consumers, as well as the small ones like you and me. Saving water and energy is a matter of solidarity. The climate change will affect all of us, but the people in the developing world are the most vulnerable. Industrial and agricultural pollution must be limited to save water resources. When leaders in the high-income world deny their role in the climate change it is a selfish attitude that will seriously hurt the weak people.

Saving water and energy is a matter of solidarity.

Communication is crucial:

- discussing the matter between friends, colleagues, neighbours;
- making groups of people meet: in study groups, between research groups, between commercial companies;
- making the water and energy economy sound: affordable for the poor and still profitable. This has been achieved in Phnom Penh, Cambodia, after long wars and serious poverty. Ek Sonn Chan (CEO, Phnom Penh Water Supply Authority) told at the 2nd IWA Development Congress in Kuala Lumpur in November 2011 about one of the results as water is delivered by piping. A 6-year old boy told him that 'before my Mother got water every 3 days. Now she forces me to wash 3 times a day.'
- The water issues in food security, human security and human development are well known by most water professionals. The issues of water security and development opportunities and international cooperation have to propagate to decision makers and even to the end users..
- *Above all*: we have to remove any fear of loss of prestige, learn from each other and try to combine our insights to make changes.

22.4.1 Urban and industrial areas

The concept of 'the city of the future' is getting attention internationally. We need to develop:

- water infrastructures for the city of the future;
- revised directives on buildings, energy labelling, and water use;
- quality-monitoring systems.

The industry needs to further:

- make a corporate commitment to both water and energy efficiency;
- educate and involve employees in water efficiency and energy efficiency efforts;
- develop new and better ways to use reclaimed water in power plants, in the process industry and in agriculture;
- develop dry cooling systems for water scarce areas.

22.4.2 Rural areas

Even if the urban population will grow faster the rural population in the developing countries will exceed 3 billion in 2020. They must not be forgotten. Many rural and under-developed areas lack any significant infrastructure for water as well as energy services. However, there are many technical solutions both for decentralized energy supply and for basic water supply and sanitation. Small scale biogas production should be encouraged. Many national and international organizations do a fantastic job to provide the basic services for human dignity. Still we need to do more: the lack of funding is embarrassing.

22.4.3 Measurements and monitoring

To measure is to know. This has been emphasized for the water system operator (Chapter 15.6) as well as for the end-user (Chapter 8.4). We need to quantify not only water and energy production and consumption but also the water-energy nexus. Already there are several organizations that provide us with relevant data, but more so in energy than in water issues:

- *On the global level*: UN via UNDP, UNEP and WWAP; Statistical yearbook from the UN Department of Economic and Social Affairs; WEC, FAO, World Energy Outlook from IEA, OECD;
- *In the U.S.*: DOE, EIA and EPA;
- *In Europe*: EU-IPPC, EEA;
- *In Asia*: Asian Development Bank (ADB) and its Asian Water Development Outlook (AWDO); UN ESCAP (Economic and Social Commission for Asia and the Pacific) and its SOE (State of Environment);
- *At national levels*: national government organisations;
- *From energy companies*: BP Energy Outlook; Exxon Mobil, The Outlook for Energy; and many others.
- Research groups at universities and research agencies.

Information on climate change is primarily available from IPCC but also from national meteorological administrations like NOAA in the U.S.

Reports from WEF (World Economic Forum) deliver interesting overviews. WWC (World Water Council) via WWF (World Water Forum) promotes awareness, builds political commitment and triggers action on critical water issues at all levels.

We need a better understanding of the water-energy-food nexus by creating a nexus of man-to-man, computer-to-computer, database-to-database, professional group to professional group, stakeholder-to-stakeholder. How do we supply measurements and statistics that can support understanding of the nexus? We need more data on water consumption and water quality consequences of global primary energy extraction as well as from electric power generation. It is also true that water quality and quantity regulations are needed in combination with fuel exploration. They also need to be enforced.

22.4.4 Water conflicts

There are many water related conflicts as told in Chapter 2. A lot of efforts are made – internationally and regionally – to find solutions to serious conflicts, but too often the root causes of the disputes come from differences in perception and needs and priorities. It is crucial to provide reliable information flows. Naturally the participation of all interest groups is important for trust building and for conflict prevention.

22.4.5 Research and development

A lot of investment on research and development (R&D) in water systems has to be done to match the increases in energy related R&D. New technology does not need to be developed in all cases. It should be identified where existing beneficial technologies are not exploited such that they can be re-examined and repackaged as 'innovative use of existing technology'.

University curricula on the water-energy nexus issues should be offered, both from an engineering point of view and from a policy-planning point of view. Why not an MSc or PhD in 'water and energy'? An encouraging sign is that several PhD projects have been started at various universities since the first edition of this book in 2012, for example at the School of Environment, Tsinghua University, Beijing. Also, new curricula in water and energy are planned, for example at the Pusan National University, Busan, Korea. There are in fact 'Power and Water Universities': one of them is located in Teheran, Iran. Other universities offer many interesting courses like renewable energy, sustainability, energy efficiency, climate change and its impact on water resources and energy production.

22.4.6 Integrated planning and decision making

From all the available data we need more tools and techniques for synthesis of measurements and for policy and decision support systems. How do we develop decision support systems that can translate data into indicators for decision/policy making? How do we assess environmental footprints of concepts and enable selection based on environmental performances together with economical evaluation (like in Chapter 10.5). This will also include:

- How to integrate energy and water availability for the poor;
- How to integrate public and private for optimisation of the water cycle;
- How to obtain a holistic management of the water and energy industry.

We need to bring the stakeholders to the table to find the relevant data, possible actions and constraints. How does the market react to the water-energy-food nexus? We may see the price for food rise because of the need for fuel. Increasing oil prices lead to bio fuel, which leads to more water use. We have to understand this dynamics. What difference does it make to have a realistic pricing of water?

22.4.7 Education

It all boils down to *education* and *inspiration* – at all levels. Conserving water will save energy and conserving energy will save water. Water and energy illiteracy are problems that have to be addressed everywhere. We have to keep informing and educating all categories: from individual consumers to political leaders, from primary school children to university students. Probably the children are the quickest learners. They can teach their parents. The children may be able to change our attitudes and habits. They are the ones that have to live with the mess that we created.

The challenges will not be solved in a few years. We can learn from the development of wind power. Denmark is a good example. It all started in 1974 when the oil crisis hit and the Danish people realized that they depended 100% on imported oil for electric energy and heating. Denmark developed a new energy policy and chose between nuclear power and renewables. Nuclear power was discarded. The knowledge of the potential of biomass or wind power was very small. From a small 22 kW windmill prototype a new wind power industry developed. A strong grassroot movement made things happen. Today Denmark has the highest share (21%) in the world of wind power. It has taken 40 years of dedicated work to come to this point.

Energy has got the attention for many years, in planning and security. Water has not got the same attention and the causal links between water and energy not only need to be understood but the nexus has to be taken into consideration in all planning, design, operation and consumption.

22.5 SOME FINAL REFLECTIONS

Water will probably be the limiting factor for our lives in this century. We simply have to get clean water to survive. Climate change is demonstrated by extreme weathers, and most of them are related to water, too much or too little. Water is needed for food production, but if the energy need competes with food production we have to handle and solve this conflict. An increasing population needs more energy, more water as well as more food on a more and more reduced area for agricultural use due to increased periods of droughts and misuse. Then, saving water and energy is a matter of solidarity. People in the developing world are the most vulnerable and often do not have the financial resources to mitigate or adapt to climate change.

Water is a crucial condition to produce or generate energy. Not only water quantity but also water quality is profoundly influenced by our energy production. It is apparent that we all have to use energy and water more efficiently. In order to motivate us we probably need both sticks and carrots. We need to find ways to encourage all of us to be more frugal to restraint climate change. We also need to motivate all of us to handle water and energy with care, for example with adequate pricing. Subsidies for fossil fuels have to be abolished and the fossil fuel industry will have to recognize their role in climate change. They will probably not reduce the fossil fuel production voluntarily, so they have to be forced. This will be a herculean task.

We have to plan for 2050 to handle the water-energy nexus. Since it takes a long time we have to start immediately. If this book can inspire you to act, then an important goal has been reached.

A1 A note on conversion of units

In 2011 only three countries – Burma (Myanmar), Liberia and the USA – have not adopted the SI (or metric) system as their official system of weights and measures. Although the metric system has been sanctioned by law in the U.S. since 1866 it has been slow in displacing the American adaptation of the British Imperial System. The USA is the only industrialized nation that does not mainly use the metric system in its commercial and standards activities.

A1.1 LARGE NUMBERS

The data about global consumption of water and energy need large numbers. There are two primary naming systems for large numbers. The USA and France (among others) use one system, while Germany, UK and other European countries use the other. In the USA 1 **billion** is 10^9 while the British name is **milliard**. One **trillion** (10^{12}) in the USA is called one billion in UK (one trillion in UK is 10^{18}). And one **quadrillion** (10^{15}) in the USA is called 1000 billions in the UK (one quadrillion in UK is 10^{24}). Here we consistently define billion as 10^9.

A1.2 POWER AND ENERGY

It is important to distinguish between power and energy. Power is energy per time unit, the rate of energy production or consumption. The SI (International System of Units) or metric unit of energy is Joule and 1 J is defined as 1 Ws (wattsecond).

1 J is the designated name for the work 1 newton · meter, in other words, the force 1 newton along the length 1 meter. The basic power unit watt (W) is defined as 1 J/s.

1 J = 1 Ws (wattsecond)
1 megajoule (MJ) = 10^6 J
1 gigajoule (GJ) = 10^9 J
1 terajoule (TJ) = 10^{12} J
1 petajoule (PJ) = 10^{15} J
1 exajoule (EJ) = 10^{18} J

Kilowatt-hour (kWh) is a standard unit of electrical energy. Since 1 kW (kilowatt) = 1000 W and 1 hour = 3600 seconds we get:

$$1 \text{ kWh} = (10^3 \text{ W}) \cdot (3600 \text{ s}) = 3.6 \cdot 10^6 \text{ Ws} = 3.6 \cdot 10^6 \text{ J} = 3.6 \text{ MJ (exact).}$$

It may be instructive to estimate the required muscle work to generate 1 kWh. Suppose that a bicycle is connected to a generator that can supply the electrical power to a 40 W lamp. A normally fit adult can keep this lamp turned on for quite some time, but it is quite demanding.

After 24 hours of continuous cycling around 1 kWh has been generated. For this energy we pay of the order 0.05 €.

1 MW (megawatt) = 10^3 kW = 10^6 W (typically, a large industrial plant or wastewater treatment system has a power rating of the order MW).

A plant with the power capacity of 1 MW will (operating at full capacity all the time) produce 1 * 8760 = 8760 MWh or 8.76 GWh (8760 hours in a year; sometimes 8766 hours are used, to include leap years).

In a thermal power plant we must distinguish between the electrical power (MWe) and the thermal power (MWth).

1 GW (gigawatt) = 10^3 MW

(a typical power capacity of a large nuclear power plant).

1 TWh = 1000 GWh = 10^6 MWh = 10^9 kWh = 10^{12} Wh

The annual electrical energy use for a nation is typically expressed in TWh. For example, all wastewater treatment in Sweden requires annually about 0.6 TWh = 600 GWh. Consequently there is an average power level of 600/8760 = 0.068 GW = 68 MW every hour of the day and night. With 9 million inhabitants every citizen uses 7.5 W at an average for wastewater treatment. About the same power and energy is used for supplying drinking water.

1 horsepower = 1 hp = 746 W

The unit toe (ton of oil equivalent) is often used to indicate large energy productions. One toe is a unit of energy defined as the amount of energy released by burning one ton of crude oil. IEA and OECD define this to be 41.87 GJ or 11.63 MWh.

1 toe = 41.87 GJ = 11.63 MWh

1 Mtoe (million toe) = 41.87 PJ = 11.63 TWh.

Note that toe should be used carefully when converting electrical units. Some reports take thermal generating unit efficiency into consideration when converting kWh to toe. With a 38% plant efficiency one toe corresponds to 16 GJ.

A1.3 PRESSURE

The metric unit for pressure is pascal (Pa), where 1 Pa = 1 Newton/m^2, which is a very low pressure. Therefore it is more common to express pressure in megapascal (MPa)

1 bar = 10^5 Pa = 0.1 MPa	1 MPa = 10^6 Pa = 10 bar
1 psi (pound/inch^2) = 6895 Pa	1 bar = 14.5 psi

A1.4 HEAT CONTENT

Before it was realized that heat was a form of energy, heat was measured in terms of its ability to raise the temperature of water. The calorie and the British thermal units were defined in this way.

- Calorie (cal): In a traditional definition one calorie is the amount of heat required to raise the temperature of 1 gram of water by 1°C, from 14.5°C to 15.5°C.
- British thermal unit (Btu) is the English system analog of the calorie.

- 1 Btu is the amount of heat required to increase the temperature of 1 pound of water (which weighs exactly 16 ounces) by 1°F.
- 1 Btu = 251.9958 cal.

In 1948 it was decided that, since heat is a form of energy, the SI unit for heat should be the same as for all other forms of energy, the joule. One cal is defined to be 4.1860 J (exactly) with no reference to heating of water. (The 'calorie' used in nutrition, sometimes called a Calorie is really a kilocalorie.)

The relationship between the kWh and the Btu depends upon which 'Btu' is used.

1 megajoule (MJ) = 10^6 J = 0.278 kWh = 947.8 Btu
1 kWh = 3412 Btu
1000 Btu = 0.293 kWh
100,000 Btu = 1 therm
1 quad = 1 quadrillion (10^{15}) Btu = 1.05506 * 10^{12} megajoule (MJ) = 1.055 EJ

A1.5 VOLUME, AREA AND LENGTH

1 US gallon = 3.78 liters; 1 UK gallon = 4.546 liters = 1.2 US liquid gallons

1 American barrel = a liquid measure of oil, usually crude oil = 42 US gallons = 159 liters

Barrel of oil equivalent refers to the energy equal to a barrel of crude oil = 5.8 ∗ 10^6 Btu or 6119 MJ

Acre-foot (the volume of 1 acre (4047 m^2 or 43560 ft^2) with the depth of 1 foot (0.305 m) is often used, particularly in the US, to denote the annual water consumption for a family or for irrigation.

1 acre-foot = 4047 $m^2 \cdot 0.305$ m = 1233.5 m^3(= 43560 ft^3 = 326,700 gallons).

1 cubic foot = 0.305^3 m = 0.0284 m^3 = 28.4 liters; 1 m^3 = 35.25 cubic feet

Dry volumes for grain: 1 bushel (US) = 35.2 liters.

Grain o corn yield is often given in the US with bushels/acre

1 bushel/acre = 0.00870 liters/m^2 = 87.0 liters/hectare
1 mile = 1609 m = 1.609 km;
1 $mile^2$ = 2.59 km^2
1 micron = 1 micrometer (µm) = 10^{-6} m
1 Angstrom (Å) (named after the Swedish physicist A. J. Ångström, 1814–1874) = 10^{-10} m;
10 Å = 1 nanometer (nm) = 10^{-9} m

A1.6 MASS

1 pound (lb) = 0.4536 kg

1 metric ton = 0.984 long ton or English ton

Gas emission is often measured in Tg, where 1 Tg = 10^{12} g = 10^6 metric tons

Natural gas is converted to barrels of oil equivalent.

1 ton of oil equivalent ≅ 1,125 m^3 of natural gas. This is based on the average equivalent energy content of natural gas reserves.

A1.7 CONCENTRATION

Concentrations are often measured in mg/l (= ppm, parts per million) = kg/m^3

A1.8 WATER USE IN ENERGY PRODUCTION/ GENERATION

In some US sources we find gallons/MBtu (millions of Btu):

1 MBtu = 293 kWh = 1054 MJ
1000 gallon/MBtu = 12.9 liters/kWh = 3.59 liters/MJ
1 liter/MJ = 279 gallons/MBtu

A1.9 ENERGY USE IN WATER OPERATIONS

kWh/million gallons:
1000 kWh/million gallons = 1 MWh/million gallons = 0.264 kWh/m^3
1 kWh/m^3 = 3780 kWh/million gallons = 3.78 MWh/million gallons

kWh/acrefoot:
1000 kWh/acrefoot = 1 MWh/acrefoot = 0.81 kWh/m^3
1 kWh/m^3 = 1230 kWh/acrefoot = 1.23 MWh/acrefoot

A1.10 SOME CHINESE UNITS

The Great Wall in China is called ‘the Ten-Thousand-Li-Long Wall’ where 10,000 li = 5000 km. The Wall is actually 6500 km. In Chinese 10,000 means ‘infinite’, and the number should not be interpreted for its actual value, but rather as meaning the ‘infinitely long wall’.

Length	***Volume***
1 zhang = 3.33 m	1 sheng = 1 liter (l)
1 yin = 33.33 m	1 dou = 10 sheng = 10 l
1li = 500 m	1 dan = 10 dou = 100 l
Area	***Weight***
1li = 6.66 m^2	1 jin = 0.5 kg = 500 g
1 fen = 10 li = 66.66 m^2	1 dan = 100 jin = 50 kg
1 mu = 10 fen = 666.66 m^2	
1 shi = 10 mu = 6666.66 m^2 = 0.667 hectare	
1 qing = 10 shi = 6.66 hectare	

A1.11 FUEL CONSUMPTION IN TRANSPORTATION

The fuel consumption for a car in Europe is usually expressed in liters per 10 km or liters per 100 km. The common unit in the USA is miles per gallon.

> 1 liter per 10 km corresponds to 1/3.78 gallons per 10/1.609 miles, so 1 liter/10 km corresponds to 23.49 miles/gallon.

Sources: CIA (2011) and the American Physical Society, http://www.aps.org/policy/ reports/popa-reports/energy/units.cfm

A2 Energy content of fuels

The energy content is defined as the energy that would be obtained as heat using a perfect combustion of the fuels with oxygen, resulting in carbon dioxide and water vapour. The standard values for fossil fuels are given in World Nuclear Organization (2010) and for biofuels in IPIECA (2012). Wikipedia is also used: http://en.wikipedia.org/wiki/energy_density.

1 MJ ≈ 0.28 kWh

Fuel	Energy MJ/kg	Energy MJ/liter
Fossil fuels		
Crude oil	42	37
Natural gas (purified)	55	0.034–0.039[a]
Coal – bituminous[b] (hard black)	>23.9	
Coal – sub-bituminous	17.4–23.9	
Coal – lignite (brown coal)	<17.4	
Gasoline	44–46	32
Diesel fuel	45	39
Biofuels		
Ethanol	29.6	23.4
Biodiesel oil	37.5	33.0

[a] Depending on the location

[b] Defined by IEA

A3

Glossary

Actuator: a transducer which reacts to a control signal and performs the desired action.

Activated sludge process: A biological wastewater treatment by which bacteria that feed on organic wastes are continuously circulated and put in contact with organic waste in the presence of oxygen to increase the rate of decomposition.

Adaptation: The process of increasing society´s capacity to cope with actual or expected changes in climate.

Aerobic: ‘with oxygen’, used for biological treatment systems characterized by the presence of oxygen, mostly as oxygen dissolved in water.

Anthropogenic: Resulting from or produced by human activities

Associated gas: natural gas which coexists with oil in a predominantly oil fields. ‘Non-associated’ gas is found in isolated natural gas fields.

AD: anaerobic digestion.

Anaerobic: conditions in a biological treatment system characterized by the absence of oxygen in any of its forms.

Anoxic: no oxygen present – nitrate instead of oxygen is used by the organisms.

Aquifer: a water-bearing layer of rock (including gravel and sand) that will yield groundwater in usable quantity to a well or spring.

Biodiesel: a diesel-equivalent, processed fuel made from the transesterification (a chemical process which removes the glycerine from the oil) of both vegetable oils and animal fats.

Biofuel: fuel produced from biomass. Biofuels include fuel-wood, charcoal, bioethanol, biodiesel, biogas (methane) and biohydrogen.

Biomass: organic matter available on a renewable basis. Biomass includes forest, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes. *Traditional* biomass refers to the use of fuelwood, charcoal, animal dung and agricultural residues in stoves with very low efficiencies.

Blackwater: water from toilets.

Bluewater: water in rivers, lakes, wetlands and aquifers that can be withdrawn for irrigation and other human uses.

BOD: biochemical oxygen demand, a measure of the organic carbon content in the wastewater. BOD5 means the BOD value after 5 days.

Brackish water: water that is neither fresh nor salt.

Carbon sequestration: The addition of a substance of concern to a reservoir. The uptake of carbon containing substances, in particular carbon dioxide.

CO_2-equivalent: See Equivalent carbon dioxide.

Combined heat and power (CHP): Combined heat and power plants refers to plants which are designed to produce both heat and electricity, sometimes referred as co-generation power stations.

COD: Chemical oxygen demand. Method of measuring the content of all oxidable substances in the water.

Cold days/cold nights: Days where maximum temperature, or nights where minimum temperature, falls below the 10th percentile, where the respective temperature distributions are generally defined with respect to the 1961–1990 reference period.

Consumptive water use: water is considered consumed when it is removed from the usable resource base for the remainder of one hydrological cycle. Evapotranspiration (see definition) is considered a form of consumption. We no longer control where evaporated water will fall next, so the water is functionally lost to the system.

Crude oil: Crude oil comprises crude oil, natural gas liquids, refinery feedstocks and additives as well as other hydrocarbons.

Denitrification: the conversion of nitrate-nitrogen to gaseous nitrogen through anoxic cell growth.

Desalination: the changing of salt or brackish water into fresh water.

Drought: A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a *relative* term; therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion.

Equivalent carbon dioxide (CO_2) emission: The amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a greenhouse gas or a mixture of greenhouse gases. See also Global warming potential.

Eutrophication: a significant increase in the concentration of chemical nutrients in an ecosystem.

Evapotranspiration (ET): the sum of evaporation from soil and plant surfaces (E) and plant transpiration (T) from the Earth's land surface to the atmosphere. The ET is crop-specific.

Exergy: of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. Exergy is the energy that is available to be used.

Evaporation: the process of liquid water becoming water vapour.

Flaring: the controlled and safe burning of gas which cannot be used for commercial or technical reasons.

Flowback: after the hydraulic fracturing procedure is completed and pressure is released, the direction of fluid flow reverses, and water and excess proppant flow up through the wellbore to the surface. The water that returns to the surface is referred to as 'flowback'.

Fossil fuel: fuels such as coal, crude oil or natural gas, formed from remains of plants and animals.

Fossil water: '*Groundwater*' that has a negligible rate of natural recharge on the human time-scale. Sometimes the term 'non-renewable water' is used.

Fouling: the process of becoming dusty or clogged, for example, in which undesirable foreign matter accumulates in a bed of filter or ion exchanger media, clogging pores and coating surfaces, thus inhibiting or delaying proper bed operation. The fouling of a heat-exchanger consists of the accumulation of dirt or other materials on the wall of a heat-exchanger, causing corrosion, roughness and ultimately leading to a lowered rate of efficiency.

Fracturing: see hydraulic fracturing.

Fresh water: water that contains only small amounts of dissolved solids.

Global Warming Potential (GWP): An index expressing the relative quantity of CO_2 that, if released into the atmosphere, would trap heat radiation in the same way as the considered greenhouse gas.

Greenwater: soil water held in the unsaturated zone, formed by precipitation (rainfall) and available to plants.

Greywater: water that becomes contaminated during a production process. Greywater also refers to domestic wastewater from kitchen, bathroom and laundry sinks, tubs and washers. Compare blackwater.

Greywater footprint: an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. Defined as the volume of freshwater required for dilution of total pollutant load to meet a defined ambient water quality standard. The treatment of greywater will of course require energy, so the greywater footprint could also be expressed by the carbon footprint for treating the greywater.

Groundwater: Water which is being held in, and can be recovered from, an underground formation. Water found in and pumped from aquifers.

Heating degree day (HDD): A measurement designed to reflect the demand for energy needed to heat a building. Heating degree days are defined relative to a base temperature. The base temperature is usually an indoor temperature (between 18°C and 20°C) which is adequate for human comfort. If the outside air temperature is lower then there is a heating requirement. The heating requirements for a given structure are considered to be directly proportional to the number of HDD at that location. A similar measurement, cooling degree day (CDD), reflects the amount of energy used to cool a building.

Horizontal drilling: an advanced form of directional drilling in which the lateral hole is drilled horizontally

Hydraulic fracturing (often called fracking): the process of using high pressure to pump sand along with water and other fluids into subsurface rock formations in order to improve flow of oil and gas into a wellbore.

Integrated water resources management (IWRM): the practice of making decisions and taking actions while considering multiple criteria on how water should be managed. This may relate to river basin planning, planning of new energy production facilities, and dam construction, and so on.

Life cycle assessment (LCA): tool for systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle.

Mitigation: ‘to make something bad less severe’. For climate change: human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Negawatt: energy saving, ‘negative energy consumption’.

Nitrification: the conversion of ammonia-nitrogen to nitrite and nitrate-nitrogen through cell growth.

Permafrost: Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

Permeability: a measure of the resistance offered by rock to the movement of fluids through it.

Produced water: water that returns to the surface along with the oil or gas pumped from the well; produced water returns to the surface after the flowback (see glossary).

Renewable resources: total resources offered by the average annual natural inflow and run-off that feed a catchment area or aquifer; natural resources that, after exploitation, can return to their previous stock levels by the natural processes of growth or replenishment.

Resilience: The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.

Reverse Osmosis: type of membrane filtration.

Salt water: water that contains significant amounts of dissolved solids.

Scaling: precipitation of solid substances on the membrane in nano and reverse osmosis filtration.

Setpoint: the desired value for a control system, that is a temperature, flowrate, pressure or level at which a process should operate.

Shale gas: natural gas that is trapped within shale (see shales) formations. Shales are fine-grained sedimentary rocks that can be rich sources of petroleum and natural gas.

Shales: a fine-grained sedimentary rock composed mostly of consolidated clay or mud. Gas reserves found in unusually nonporous rock located far below ground require special drilling and completion techniques.

Surface water: water pumped from sources open to the atmosphere, such as rivers, lakes and reservoirs.

Unconventional oil or gas resources: reservoirs of natural gas or oil, in geological formations with often extremely low permeability, which are unable to flow readily to the wellbores. Examples include: heavy oil, oil sands or tar sands, tight oil, oil shales, tight gas, shale gas, and coalbed methane.

Volatile organic compounds: VOCs are ground-water contaminants of concern. They are organic chemicals that have a high vapour pressure at room-temperature conditions. This causes the chemicals to evaporate and enter the surrounding air.

Warm days/warm nights: Days where maximum temperature, or nights where minimum temperature, exceeds the 90th percentile, where the respective temperature distributions are generally defined with respect to the 1961–1990 reference period.

Water abstraction: see ‘water withdrawal’.

Water consumption: volume of surface or groundwater withdrawn that is not returned to the original water source and therefore is no longer available for reuse.

Water footprint (WF): the term is defined in different ways. Here we define it according to www.waterfootprint.org: ‘the direct water footprint of a consumer or producer refers to the freshwater consumption and pollution that is associated to the water use by the consumer or producer.’

Water intensity: the ratio of water withdrawn or consumed to the unit of energy that is produced, for example liters/kWh or m^3/MWh or m^3/GJ and so on.

Water scarcity index: often expressed as the ratio between gross water abstraction and total renewable water resources.

Water stress: the Falkenmark (see Falkenmark, 1989) water stress indicator defines the following thresholds in m^3/cap/year: <500: water availability is a main constraint to life; 500–1000: water scarcity is a limitation to economic development and human health and well-being; 1000–1700: water stress appears regularly; >1700: water shortage occurs only irregularly or locally.

Water withdrawal: the volume of freshwater abstraction from surface or groundwater. Part of the freshwater withdrawal will evaporate, another part will return to the catchment where it was withdrawn and yet another part may return to another catchment or the sea.

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'Professor Olsson's book, Water and Energy Threats and Opportunities, the result of a meticulous multi-year effort, meets an important and growing need: to define and illuminate the critical linkage between water and energy. He explores the water-energy nexus in detail, and carefully discusses its many implications, including for food production and its connection to global climate change. He properly and repeatedly emphasizes the important message that water and energy issues must be addressed together if society is to make wise and efficient use of these critical resources. Given its comprehensive scope and careful scholarship, the book will serve as a valuable addition to the libraries of students, researchers, practitioners, and government officials at all levels. In its expanded and updated second edition it adds a clear and comprehensive discussion of the important subject of fracking which has recently emerged as a major public issue.' Dr. Allan R. Hoffman, Senior Analyst, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC

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