Water in the energy industry An introduction



Water use in major energy production pathways, highlighting the extraction of the resource and the subsequent processing to create a commercial product. Indirect water use for fabrication of materials (e.g. steel, silicon) and equipment (e.g. drills, turbines) used in extraction and processing is not included here, nor is any water use in transportation to the end user.



Water in the energy industry An introduction



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Professor Ellen Williams

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Foreword by Ellen Williams

BP Chief Scientist

Energy is essential to human civilization, and the production of energy and electrical power is dependent on water in many ways. The possible impact of regional water scarcity on choices about energy production is one of many questions being addressed in BP's Energy Sustainability Challenge programme (www.bp.com/ energysustainabilitychallenge), a collaboration among researchers from 13 leading universities. Their work has contributed trusted data on the implications on land, minerals, water and ecosystems of different energy pathways, and the sensitivity of these to changing patterns of demography, climate and natural resource governance.

This short book is about the changing ways that we humans use water to help us obtain energy in the forms we need. Not so long ago, even within the past century, when we needed water, we largely just took fresh water from the most convenient well, river or lake, consumed some and discarded the rest, often with significant accompanying pollution. With our increasing population and quality of life, such careless use of fresh water is not sustainable.

Fortunately, there are many ways to retain the benefits of water for energy production while reducing the impact on the world's freshwater reserves. These can be summarised as 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.

Each of these opportunities finds applications in different ways in different parts of the energy cycle, and in different parts of the world. All can be improved with scientific and engineering advances, and all require choices about investment priorities.

In the chapters of this book, we will repeatedly see ways to decouple water use for energy generation from the local renewable freshwater reserves. We also will consider water quality issues and the energy cost of providing and treating wastewater. The potential good-news story about water use for energy will depend on human decisions and priorities to become a worldwide reality.

Foreword by David Victor

Director, Laboratory on International Law and Regulation, University of California, San Diego

For years, pundits have been predicting that water will be the next big environmental challenge. Yet these worrisome visions have not been matched by much useful data because the barriers to measurement and analysis are daunting. Analysts often haven't agreed on basic concepts such as what actually counts as 'water use' in statistics. With so many disagreements, very few studies have carefully assessed the actual fresh water withdrawn or consumed by different technologies in ways that could help policy makers and the public make reasoned choices.

This timely new handbook from BP helps set some records straight. It focuses on how the energy business intersects with water, which is apt since energy (usually after agriculture) is perceived to have a big impact on water.

One striking result from what follows is that the potential for managing the implications on water of the world's growing demand for energy is massive. Existing technologies already vary by orders of magnitude in their freshwater withdrawal, and the potential for adapting technical approaches to match regional needs is huge. That suggests that if water crises actually unfold in energy delivery, it is likely they will be the result of failures in governance rather than the lack of technology. Fixing these governance issues is a national, regional and local matter since there's no global scheme that will work in every setting.

Another striking result is that the big push in biofuels that is now under way could go either way for water and land and resources. The best examples of biofuels use crops that are grown in areas where little or no irrigation is needed, and make use of otherwise under-utilized lands. Poor implementation, however, can cause serious impacts on both the water and land fronts. Careful governance and technical innovations in biofuels are essential if that technology is to scale up in environmentally sustainable ways.

This study shows why analysis is so important, and it also helps reveal the new challenges for those who study water-energy interactions. The handbook shows how it is possible to do a lot better in studying the volumes of water withdrawn and consumed by energy systems, as well as the energy used in water delivery. Much harder to study is water quality, such as chemical and temperature pollution. Also critical is to understand the interactions between what humans use for themselves and what is left for nature. For example, where I live in California, it is the need to set aside bigger volumes of better water for nature that is our central future challenge.

Many regions face looming scarcities of water, and climate change could make that a lot worse. But unlike climate change, where it has proved difficult and costly to make much of a dent, fixing the world's water-energy problems is readily in our grasp. In the chapters that follow, we will provide a technical lens on freshwater use in energy production, starting with the concept of withdrawals and consumption of water, and using 'freshwater intensity' as the metric for both.

- Freshwater withdrawal, as its name implies, simply quantifies the amount of fresh water removed from local sources, independent of its later fate.
- Freshwater consumption quantifies the amount of fresh water that is withdrawn but not returned to the local water basin as fresh water.
- Water intensity is the ratio of the volume of water withdrawn or consumed to the unit of energy that is produced. This requires us to think quantitatively about volumes, and about energy units for different forms of energy.

Notes on quantifying how we use water for energy

Volumes

We will measure volumes of water in cubic metres (m³) as illustrated in the volumes chart, on page 8. This might not seem like a large amount, but a cubic metre of water weighs a metric tonne. Worldwide water use is so large that we will sometimes express water quantities of a billion m³ as one cubic kilometre (km³). Keeping this in mind, the world has available about 40,000 billion m³ (40,000km³) of renewable fresh water per year. Of this, we (the human race) now withdraw about 10%, which is about 4,000km³ per year, and consume much of this.

Energy

We will report energy in the scientific unit, joule (the international standard, www.bipm.org/en/si), as indicated in the energy chart on page 9, distinguishing the applications of thermal energy (J_t), electrical energy (J_c) and the calorific energy from agricultural products (J_c). A joule is a relatively small amount of energy, so to keep our numbers manageable, we will use millions of joules (MJ = megajoule), billions of joules (GJ = gigajoule) and trillions of joules (TJ = terajoules = a thousand billion joules). To provide a sense of scale for terajoules (TJ), we can look at thermal, electrical and caloric examples:

- **Thermal**: thermal energy is the energy that can be released as heat on burning fossil fuels or biomass such as wood. A TJ of thermal energy can be obtained from burning about 28,000 litres (about 7,300 US gallons) of gasoline (petrol). This is enough to drive about 20 moderately efficient passenger vehicles 15,000km (about 10,000 miles) each. Overall, the world's primary energy use was just over 500 million TJ in 2010, and about 40% of that was used in the production of electrical power.
- **Electrical**: primary energy is used to create electrical energy at about 30 50% efficiency. This means that $1TJ_t$ of primary energy can yield $0.3 0.5TJ_e$ of electrical energy. One half (0.5) of a TJ_e is enough to light 150 100W light bulbs for one year. Overall, the world's use of electricity in 2010 was 64 million TJ_e .
- **Calorific:** the energy that human beings derive from food is not generally included in tabulations of world energy use. Nevertheless, it is energy, and it is typically measured in units of Calories where 1 Calorie = 4,184 joules (this dietary Calorie should not be confused with a calorie, which is equal to 4.184 joules). Well-nourished people may have a diet of around 2,500 Calories per day. This means that a TJ of calorific energy ($1TJ_c$) could provide all the food energy for a year for 260 people.

Water intensity

Now that we have some insight into the measures for volumes of water and amounts of energy, we can consider the water intensity. This is expressed in cubic metres of water per TJ of energy (m^3/TJ) , which isn't an intuitive unit. So to place in context the scale of the numbers we will deal with, we'll consider three categories: production of primary fuels, generation of electricity and production of food Calories.

- For primary fuels, another useful measure is to compare the volume of water per volume of the fuel produced. If one volume of water is used to produce one volume of a fuel, such as gasoline, this is equivalent to a water intensity of about 28m³/TJ.
- For generation of electricity, because conversion is inefficient, we use water to carry away waste heat. For instance, at 50% efficiency, to carry away 0.5TJ of waste heat by warming a stream of water, one would withdraw 10,000m³ of water or more, giving a water-withdrawal intensity greater than 20,000m³/TJ_e. To carry the same heat away by vaporizing water into steam, one would consume 200m³ of water for a water-consumption intensity of 400m³/TJ_e.
- The water intensity scale for food Calorie production can be defined in terms of the world's water consumption for irrigation (70% of human freshwater withdrawals) and the dietary demands of about seven billion people. The resulting water intensity is about 50,000 100,000m³/TJ_c.

Each of these numbers, summarized in the table below, illustrates a size scale based on what we need to accomplish with the water (not necessarily all fresh water) used in energy production. Keeping in mind the four Rs of replacement, reuse, recycling and regional responsibility, we can use these size scales to help understand how evolving practices can reduce the impacts of energy production on the world's renewable freshwater reserves.

Energy type	Water impact	Scale of water intensity (not necessarily all fresh water)
Fuel production (primary energy)	Consumption	Tens of m³/TJ _t
Electrical generation	Consumption Withdrawal	Hundreds of m³/TJ _e Tens of thousands of m³/TJ _e
Food Calories (agriculture)	Consumption for irrigation	Up to a hundred thousand m³/TJ _c

Units of volume



Units of energy



- Globally, a little more than 4,000km³ of fresh water is withdrawn each year for human use. Of that, about 70% is withdrawn for agriculture and around 10% for the power industry.
- Definitions are important. Withdrawal is fresh water removed from surface or groundwater at least temporarily. Consumption is fresh water withdrawn but not returned within the same drainage basin.
- When choosing technologies or setting policy, it is vital to distinguish between withdrawal and consumption, and where fresh water is or can be reused or replaced with lower-quality water.
- The keys to reducing the impact of energy and power production on the world's renewable freshwater reserves are replacement, reuse, recycling and regional responsibility.

1 Introduction

This introductory chapter sets the context for understanding the volumes of water withdrawn and consumed in producing the energy that powers modern civilizations. The starting point is to appreciate the volumes of water on earth and the hydrological cycle that creates a renewable supply of fresh water. Although the renewable freshwater resource is, on average, sufficient to offer everyone sufficient water for basic needs, the unequal geographical water distribution results in two billion people living in areas where there is insufficient water or areas of fresh water scarcity.

Where sufficient water is available, humans have been using it to improve their lives for at least 7,000 years and today we withdraw a little more than 4,000km³ or about 10% of the renewable freshwater resource. About two-thirds of that is used for agriculture, about one-fifth for industry and about one-tenth for domestic use. Of the industrial water withdrawals, about two-thirds are related to energy and power production.

Energy and water

In 1751 a 15-year old boy was chastised by his cousin for spending the afternoon watching steam rise from a kettle and condensing on a silver spoon. The family members around the fireside didn't realise that what was happening in their kitchen that day would impact the most important invention of the 18th century, and help to change the world. The boy was James Watt and his condenser, based on thoughts born when watching the kettle, tripled the efficiency of the steam engine and laid the foundation of the industrial revolution. Watt's historic contribution is just one aspect of the relationship between water and energy. Water as a source of energy has been well documented since at least Roman times, with water wheels powering machines as diverse as clocks and corn mills^[1]. Miners have always used water to wash ores, and smelters and metalworkers have needed water for cooling since these industries originated. Today, washing and cooling are processes at the heart of most heavy industries and, in addition to water for power, access to water has been a key factor in the development of industrial economies. These industries also affect the quality of water available for human consumption and for ecosystems that depend on clean water.

The multiple uses of water by the energy industries are outlined in the figure on the inside front cover, which sets the stage for more detailed discussions in subsequent chapters of this book.

Water and the hydrological cycle

To a good approximation, no water is leaving the planet and none is being added, although water molecules can be formed and transformed in a variety of ways. The total water that circulates, including in the oceans, rivers, lakes and ice caps, plus in all plants and animals, is collectively known as the hydrosphere. The vast majority of the hydrosphere, more than 96%, is contained in the oceans. Of the remainder, shown in Figure 1.1, some 2% is in ice caps and glaciers and less than 1% is in fresh groundwater in aquifers (geological formations of sand, gravel and rock where groundwater is stored between grains and in rock pores)^[2]. The fresh water that we normally think of as being easily accessible – in rivers and lakes – constitutes only 0.01% of the total water on earth.

Figure 1.1

Saline and fresh water on earth: the cubes illustrate the relative world total volumes. Seawater, which accounts for 96.54% of all the water on earth, is not shown. Percentages are shown for freshwater volumes only.^[3]



Most of the water in the hydrosphere is in constant motion, driven by energy from the sun – the hydrological cycle. Solar energy evaporates water at the surface of the oceans, rivers, lakes, swamps and soils, and plants draw up water from soils and pass most of it out to the atmosphere in a process called transpiration. When the water vapour in the atmosphere condenses, clouds form and precipitation, either as rain or snow, occurs. The atmosphere contains only around 12,900km³ of water at any one time, but global average annual precipitation is estimated at 111,000km^{3 [4]} indicating the cyclic nature of the freshwater resource.

In addition to the interplay of precipitation, evaporation and transpiration, the hydrological cycle is completed with a number of different water migration mechanisms: recharging groundwater, groundwater flow and discharge, snow melt and surface runoff. Water that falls on land can infiltrate the soil and rocks, becoming groundwater. Groundwater that does not return to the atmosphere by evaporation from soils or transpiration through plants can return to the surface via springs (when the water table intersects the surface) or directly discharge into bodies of water.

Water that does not infiltrate the ground is called runoff and can collect into streams or rivers. The time that water stays in a particular part of the cycle, known as the residence time, varies enormously from a mean of twoand-a-half weeks in rivers, to hundreds or even thousands of years in some aquifers. Water in aquifers that does not recharge on a human time scale can be regarded as nonrenewable.

The renewable fresh water provided by the hydrological cycle is illustrated in a Sankey diagram^[5] in Figure 1.2. Starting at the left, the distribution of rainfall among the

continents is illustrated, with the numbers indicating the volume of fresh water measured in km³. Of that water, the majority falls on forests, followed by grasslands, cropland and other land types ^[4]. From these landmasses, more than half the water returns to the atmosphere through the process of evaporation and transpiration (evapotranspiration), and the rest is distributed in surface waters and recharge of groundwater. As shown at the right of Figure 1.2, the total difference between annual precipitation and evapotranspiration, which is known as the renewable freshwater resource (RFWR), is estimated at about 40,000km³ ^[6]. This is the maximum amount of water available to support the world's aquatic ecosystems and, simultaneously, to provide for human needs.

Water withdrawals

The worldwide renewable freshwater resource shown above is not uniformly available: there are large regional variations in water availability and human demands for water. One way the extremes of regional variability can be illustrated is with a comparison of local human withdrawals of water to the renewable water available in the local watershed, a metric called the water scarcity index (WSI):

Water scarcity index (WSI) =

Annual freshwater withdrawal Local renewable freshwater resource (RFWR)

The geographical variation is illustrated in Figure 1.3 on

the next page, with a colour scale from white or blue for low water scarcity to red or black for high. Regions where human withdrawal of fresh water is more than 40% of the RFWR (WSI greater than 0.4) are considered highly water stressed.

Figure 1.2

Global freshwater Sankey diagram for annual precipitation over land ^[5]. From left to right, the diagram illustrates the continental distribution of rainfall, the land types on which rain falls, the services provided by the water, and finally the distribution of the water between the atmosphere (through evapotranspiration), fresh surface and groundwater. The vertical width of each bar in the diagram is proportional to the volume of fresh water involved, measured in cubic kilometres (km³), and numerical amounts are provided with labels, also in km³. Polar regions not included.



Figure 1.3

Global water scarcity index. Water scarcity is indicated on a scale of 0-1. Regions with an index of 0.4 or greater are considered to be highly water stressed ^[4].



The global human withdrawals of water that underpin the water scarcity distribution are illustrated in another Sankey diagram, Figure 1.4. About two-thirds of human freshwater withdrawals are used for agriculture, the majority in Asia. A little more than half the water withdrawn for agriculture is returned to the atmosphere through evapotranspiration. The rest is returned to surface and groundwater, carrying varying amounts of contaminants, including fertilizer that can cause excessive nutrient input and possibly lead to algal blooms and oxygen depletion in bays and estuaries^[7]. About 19% of the withdrawals are for industry, and half the water withdrawn for industrial use is for cooling. This water, minus some losses to evaporation and with some limited material contaminants added, is returned to waterways at a higher temperature, which can affect aquatic ecosystems. The remaining industrial effluent and returns from the domestic sector can carry significant contaminants, and are discharged to surface water bodies or groundwater. There are strong regional variations in the level of wastewater treatment.

The element of the Sankey diagram labelled 'energy' is the focus of this book. The 470km³ of water indicated is about 12% of all withdrawals. This water ultimately is evaporated, returned to the hydrological cycle as warmer water, or exposed to variable levels of contaminants and post-use treatment.

Figure 1.4

Global Sankey diagram for annual water withdrawn for human use^[5]. From left to right, the diagram illustrates the continental distribution of withdrawals, the sectors (agriculture, industry, domestic) in which the water is used, the services provided by the water, and finally the return of the water to the hydrological cycle. In the final (right-hand) segments, changes in water quality during its use are indicated in different colours. The red segment indicates where energy is used in treating wastewater. The vertical width of each bar in the diagram is proportional to the volume of fresh water involved and numerical amounts are provided in km³.



Chapter summary

Fresh water, a resource present on earth in sufficient quantity for all human needs, is distributed so unequally that more than two billion people live in areas of water stress. Shortages cause hardship and without constructive action will increase with increasing population, climate change and improving quality of life in developing countries. Humans interrupt the process that circulates water around the earth by withdrawing about 4,000km³ of fresh water annually. About two-thirds of withdrawals are used in agriculture, compared with one-ninth for the entire energy industry. It is important when considering any water-related topic to distinguish between withdrawal, use and consumption. It is also important to distinguish the quality of the water that is used and the quality that could be used. Formal definitions of water quality in terms of total dissolved solids (TDS) are provided in the glossary.

Understanding how and why water, both fresh and non-fresh, is used in industrial, agricultural and domestic settings is the first step in choosing methods and technologies that can reduce freshwater withdrawal and consumption.

Preview of following chapters

In the following chapters, we will describe how water is withdrawn and consumed in the extraction of energy resources (fossil fuels, uranium and agricultural products for biofuels), following the outline shown inside the front cover. Two types of processing will be presented: refining (to transform raw products to commercial products) and power generation (in which energy sources are used to deliver electricity). Finally, we will review the use of energy in delivering the water that is withdrawn and in treating it for disposal after it is used.

Definitions

Misunderstandings about water often stem from a lack of common terminology and the use of vague wording such as the amount of water 'used', or the amount it 'takes' to produce everyday food or goods. Some of the greatest confusion arises when not considering the distinction between water use, withdrawal and consumption:

- Water use: the non-technical understanding is quite different from the engineering definition. In engineering, the same water can serve several functions in a process, and each will be counted as a 'use'. As a result the amount of water used in the engineering sense can be many times larger than the amount of water withdrawn.
- Withdrawn water: water removed from surface or groundwater, at least temporarily, to produce or process energy or for some other purpose. Water withdrawals are typically classified as either surface (from river, lakes or impoundments) or groundwater withdrawals.
- **Consumed water**: consumption is the portion of withdrawn water not returned to the surface or groundwater in the same drainage basin from which it was abstracted. Consumed water is evaporated, transpired, incorporated into products or crops, or otherwise removed.

The striking differences between percentages of total water withdrawal and total water consumption are illustrated in Figure 1.5 for water in the US. While water withdrawals for cooling in thermoelectric power generation are a large fraction (near 50%) of total withdrawals, they represent only about 3% of US water consumption.

Figure 1.5



Estimated freshwater withdrawal and consumption in the US, 2005 ^[8-9]. The ratio of withdrawal to consumption is higher in the US than the world average.

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2 Water in fossil fuel and uranium extraction

Introduction

Through mining and drilling operations, humanity has access to the mineral wealth of the earth's crust, down to a depth of around 10 kilometres below the surface (see Figure 2.1, overleaf). Energy in abundance can be found in fossil fuels and radioactive minerals. The fossil fuels – coal, oil and gas – are hydrocarbons that essentially store solar energy accumulated through millions of years of plant growth in the geological past. The primary radioactive mineral used for energy production is uranium.

The volume of solid and liquid energy materials extracted from the crust every year is enormous. In 2011, energy industries extracted about 8.5 billion m³ (7,800Mt^[1]) of coal, 4.5 billion m³ (4,000Mt^[1]) of oil and 2,900m³(55Kt^[2]) of natural uranium metal. Combined, that mineral pile would be enough to build the great pyramid of Giza 5,000 times.

Energy content^[3]

For fossil fuels, the energy content is defined in terms of the energy that would be delivered as heat in perfect combustion of the fuels with oxygen to form carbon dioxide and water vapour. Standard values for crude oil, natural gas (purified) and coal are:

Crude oil		42MJ/kg
Natural gas		55MJ/kg
Bituminous (hard black coal)	>	23.9MJ/kg
Sub-bituminous coal		17.4-23.9MJ/kg
Lignite (brown coal)	<	17.4MI/kg

For uranium, the energy content is defined in terms of the thermal energy that can be captured from radioactive decay in a standard commercial reactor. The mass of uranium is generally expressed as the mass of the naturally occurring isotopic mix of pure uranium, or as the mass of pure uranium that has been enriched in the radioactive isotope, U²³⁵:

Natural uranium	500GJ/kg
Uranium enriched to 3.5% U ²³⁵	3,900GJ/kg

The withdrawal and consumption of water in these extraction processes is the topic of this chapter. We will begin with an outline of general processes that are common to the extraction of more than one of the different energy materials. Then the extractive processes and associated water-use issues will be described in separate sections for each of the energy materials:

- Conventional oil.
- Unconventional oil.
- Conventional gas.
- Unconventional gas.
- Coal.
- Uranium.

We conclude with an estimate of the global withdrawal and consumption of freshwater for the extraction of energy materials. While many opportunities remain to reduce water withdrawals, primarily by replacement with brackish, sea or produced water, the estimated amounts at present range up to about 9km³ per year, significantly less than half a per cent of the worldwide freshwater withdrawals.

As described in the introduction, in reporting fresh water for energy extraction, we will focus on two types of freshwater intensities:

- The volume of fresh water **withdrawn** from the local surface or groundwater sources per unit of energy developed is the freshwater withdrawal intensity, expressed in m³/TJ.
- The volume of fresh water **consumed** (withdrawn water that is not returned to the same basin from which it was withdrawn) per unit of energy developed is the freshwater consumption intensity, also expressed in m³/TJ.

Common processes

Exploration

Exploration for underground energy resources starts with geological and geophysical surveys to identify areas of interest. These investigations require water only for human consumption and vehicle use, so the water impact (typically less than 1,000m³ for an entire survey programme) is negligible in terms of the final water intensity.

Mining - extraction of solid fuels

Surface mining

When minerals are close to the surface they can be reached with open mines. Open pits are basically enormous holes - mines where layers of soil and rock ('overburden') are removed from a known area of mineral, which is then extracted, leaving a hole to be filled in or abandoned. If open pits are holes, opencast mines are giant trenches, suited to flat-lying sheets of mineral such as coal seams or oil sands. Long cuts are made to expose the mineral. with the overburden temporarily stored behind the cut. Once the mineral has been extracted, that part of the cut is filled in with overburden dug from a new cut. This process continues to the boundaries of the mine and then the final cut is filled in with the original store of overburden. Restoration of a mine site to a natural state is often possible after operations are complete, although this was rarely done in the past.

Open mines vary widely in size, from small uranium mines only a few metres deep and wide in southern Africa, to coal mines in Wyoming, US, and oil-sand mines in Alberta, Canada, that are measured in square kilometres.



Drilling muds are expensive to produce, so they are constantly recirculated in the well and recycled for use in other wells. When no longer needed, oil-based muds may be recycled by the manufacturer, and water-based muds are treated for disposal. Solid cuttings are removed and allowed to settle in tanks or pits prior to treatment and disposal (see dealing with wastewater below).

Oil and gas flow to the surface

Production is the industry term for bringing oil and gas to the surface. Once a reservoir is penetrated by a well, any pressure in the reservoir above hydrostatic pressure will cause fluids to flow up the wellbore. If the pressure is not sufficient, oil has to be pumped or lifted, or pressure increased by fluid injection. As the field matures, secondary recovery and tertiary (enhanced oil recovery, or EOR) methods are employed. In some of these cases, fluids (e.g. water) or gases (e.g. CO₂) are pumped into the ground to manipulate fluid pressures and properties (e.g. viscosity), thereby releasing additional liquid hydrocarbons. These techniques, and their water implications, are described in the conventional oil section beginning on page 21.

Figure 2.4

Schematic illustration of the flow of water-based drilling mud in exploration appraisal, development and production wells (not to scale). Water and chemicals are mixed to create mud, which circulates down the well and then back up to the surface. Cuttings are removed at the surface, and the mud is treated prior to recycling back to the original well, or for reuse in other wells. The volume of mud must be sufficient to fill the entire wellbore.



Hydraulic fracturing

Oil and gas can be produced from reservoir rocks that have very low permeability by hydraulic fracturing (commonly known as fraccing). In hydraulic fracturing treatments, a fluid is pumped at high pressure down a wellbore to initiate and propagate cracks in the lowpermeability rock. The fluid is often a freshwater-based mixture containing sand or other solids, called proppants, that can prop open the newly created fractures. The water implications of hydraulic fracturing are described in the unconventional gas section.

Water extracted with energy materials

Oil and water do not form a solution, but in nature they are often intimately associated. Water trapped in rocks when they were formed is known as connate water. This water is present in the pores of the reservoir rocks that contain oil and gas, as illustrated in Figure 2.2, and fills the pore space of rocks below the hydrocarbon reservoirs. Produced water is the term used to describe water extracted at the same time as oil and gas. Most produced water is saline and also contains traces of hydrocarbons. Production chemicals and heavy metals in solution may also be present; in some cases, the water may also include small amounts of naturally occurring radioactive minerals from the rock through which it flowed.

For gas, connate water can be brought to the surface in the vapour phase and condensed as process fluids are depressurised and cooled. The condensed water is not saline but may contain hydrocarbon contaminants.

Coal also often contains trapped water, which when recovered from coal will contain coal dust as well as mineral contaminants, variable levels of salinity and possibly some hydrocarbons.

Dealing with wastewater

Wastewater from production of underground energy resources requires treatment to remove contamination or special disposal techniques. In some settings, wastewater can be disposed of in injection wells drilled for this purpose. These wells may be associated with liquid hydrocarbon production or may be dedicated disposal wells drilled down to suitable rock formations.

If injection is not an option, the wastewater must be treated. Wastewater can be held in vessels or ponds where suspended solids drop out and oils float to the surface and can be skimmed off. Chemical additives can be introduced to encourage flocculation, which is the coagulation of small particles into clumps big enough to settle. These treatments can raise water quality to standards that permit discharge, or prepare the water for subsequent reuse.

The salinity of produced water limits economic reuse. Evaporation is a simple method of reducing saline water volumes, leaving concentrated or solid residues for disposal in specially designed landfills or disposal wells.

Conventional oil - the primary source of transportation fuels

Surface oil seeps led, centuries ago, to hand-dug wells in Azerbaijan and, possibly, to oil being extracted via wells drilled with bamboo rods in China. Oil was used mainly for fuelling lamps until the invention of the internal combustion engine. This did to oil demand what the steam engine did to coal, and the oil industry owes its size to human thirst for transport fuels and for the many products derived from petrochemicals.

The term 'conventional oil' is applied to oil reservoirs, both onshore and offshore, in which all fluids (oil, gas and water) can relatively easily flow through the reservoir rock pore spaces (see Figure 2.3), and can be produced with techniques that have evolved directly from the early days of oil and gas production.

Crude oil composition and energy content ^[3, 6, 7]

Crude oil is an organic liquid substance found in geological formations beneath the earth's surface. Oil is conventionally extracted by drilling wells in the ground. It consists of a mixture of liquid hydrocarbons (84 - 87% carbon and 11 - 14% hydrogen) with associated impurities such as sulphur (0 - 6%), oxygen (0 - 2%), nitrogen (0 - 1%) and heavy metals. Conventional oil always contains dissolved natural gas and is generally produced along with connate water. Unconventional sources of oil are oil sands, tight oil (or shale oil) and heavy oil, all of which require more complex extraction methods.

A standard value used for the energy content of conventional crude oil is a tonne of oil equivalent energy (toe) where 1 toe = 42 billion joules/tonne (42GJ/t). Amounts of oil are often measured in barrels and tonnes. World oil production in 2011 was 3,995 million tonnes (= 30.5 billion barrels) of which around 5% came from unconventional oil sources.

Figure 2.5

Schematic illustration of conventional oil production onshore and offshore.

The facilities are shown at larger scale than the geological features, and different sedimentary rock types are indicated by shades of grey and brown. Vertical scales subsurface range down to around 10,000 metres and offshore water depths can reach approximately 2,500 metres.

Offshore production is shown from a semi-submersible production platform with waterflood operations, shown here with water injection into the oil-associated aquifer, and a sea-floor pipeline to the onshore processing facility. Onshore, wells are shown with pump jacks/nodding donkeys, as well as with submersible pumps.

(This illustration is not to scale and is purely representational.)



Conventional oil and gas extraction processes

All oil exploration and production operations use wells, which form conduits from the surface into the target reservoir. Figure 2.6 shows where in the production process water is used. It is still not uncommon to use some fresh water from surface or groundwater sources. Improved production techniques, however, greatly reduce freshwater consumption, as will be described in the section below on water volumes.

Primary production

During its initial operational phase, a conventional oil reservoir typically has sufficient natural pressure for the reservoir fluids to flow from the reservoir rock into the wellbore and up to the surface. In some cases, pumps are used to help lift the oil to the surface. As reservoir fluids are produced, the pressure in the reservoir drops, requiring injection of fluids to maintain pressure and production rate. The primary production phase can span many years or even decades.

As illustrated in Figure 2.6(a), primary production brings associated gas and water to the surface, and a separator unit at the surface yields three output streams (oil, gas and water). The produced water can be re-injected into the reservoir, disposed of in injection wells or treated for other disposal (see disposal section below). Re-injecting produced water, which can be supplemented by additional water sources, is an effective method of maintaining reservoir pressure. Typically, injection volumes need to equal or slightly exceed the volume of oil plus produced water to maintain the reservoir pressure.

Secondary production

Secondary oil production generally refers to the point after which simply maintaining reservoir pressure is insufficient to sustain economic rates. At this point, new wells can be drilled to inject water (or other fluids) into the reservoir to drive oil towards the production wells. This technique, generally known as waterflooding, can significantly increase the percentage of oil recovered.

The waterflood process is illustrated in Figure 2.6(b). Fluids from the production well are separated as in primary production. The injection well is positioned some distance from the production well, with the position chosen based on an understanding of the reservoir characteristics. The injection water may be obtained from seawater, reuse of produced water, from purpose-drilled brackish water wells, from freshwater sources or from municipal wastewater sources. Seawater is typically used offshore, or at onshore sites near the coast. Before using seawater, sulphate ion concentrations are typically reduced to mitigate bacterial production of hydrogen sulphide.

Whatever mixture of water sources is used, the water is generally treated before injection to reduce the potential for microbial activity in the reservoir and because the clays and other minerals often present in reservoirs are sensitive to the salinity, hardness and other chemical attributes of injected water. Inappropriate composition of injected water can cause clays to swell or deposit and block the passages between pores, effectively reducing (or even removing) permeability. Also, salts within reservoir fluids can be precipitated as scale in the production pipework.

Tertiary production

As a field matures, a variety of tertiary, or enhanced oil recovery (EOR) techniques may be used to extend the field's economic life. These techniques often involve injecting water combined with chemical additives and/or hydrocarbon gases or CO_2 into the reservoir, as illustrated in Figure 2.6(b). This injection provides pressure support while lowering the viscosity of the remaining oil or reducing its tendency to bind to the rock fabric. In some fields, water injection is alternated with periods when natural gas, other hydrocarbon or CO_2 is injected, in a process known as water alternating gas (WAG).In some scenarios, special additives are used to block high permeability paths to force water into other parts of the reservoir.

Produced water, treatment and disposal

Produced water varies greatly from field to field in terms of volume and chemistry. Generally, as a field matures, the ratio of water-to-oil produced will tend to increase as oil production decreases. In mature fields, water can comprise more than 90% of the fluids produced by wells. Estimates of the ratio of the volume of produced water to the volume of oil produced vary from less than 1:1 in the United Arabic Emirates^[8], still relatively immature with its field developments, to 11:1 in the more mature and depleted fields in Canada^[9].

Most of the produced water is separated from the fluids reaching the wellheads. In some cases, the produced fluids are heated, or treated with de-emulsifier chemicals, to help separate the oil and water. The separated produced water can contain naturally soluble reservoir minerals, chemicals used for field operations and very fine rock particulate (sand), as well as free, dispersed and dissolved hydrocarbons. Before re-injecting the water, particulates and any oil-related residues (greases) are filtered out.

For any produced water that is not re-injected, responsible field operations (reinforced by regulation) increasingly require treatment to specified standards before discharge into surface water bodies, such as lakes or rivers. Alternatively, disposal of produced water via injection wells is a common practice. In some cases, lined surface pits are designed and maintained to evaporate the field-operations water while protecting local aquifers. The remaining sludge is monitored and eventually disposed of according to regulatory practices. If surface discharge methods are necessary, strictly regulated monitoring programmes are implemented to ensure disposal compliance.

Figure 2.6a

Schematic flow diagrams for water use in oil production (not to scale).

Diagram (a) illustrates the primary production process where reservoir fluids, oil, gas and connate water reach the surface through the production well and enter a separator. From the separator, the gas and oil are piped for export and the produced water is either pumped back into the reservoir, through the injection well (shown here with injection directly into the oil zone to maintain pressure), injected into non-potable aquifers for disposal or piped to other disposal facilities.

a Primary production



Figure 2.6b

Diagram (b) illustrates the secondary and tertiary production processes. Oil, gas and water reach the surface through the production well shown on the right of the diagram and enter the separator. Oil and gas are exported and the produced water is either pumped off for treatment and disposal, or piped to the injection unit for combination with fresh water and/or treated saline or brackish water. Hydrocarbon gases and/or CO_2 can also be combined in this unit to further facilitate oil recovery. The combined fluid is injected under pressure into the reservoir.



Volumes of water

Considerable volumes of water can be required for the effective operation of conventional oil fields, but there is generally little need for the source to be fresh water. Therefore, if the majority of produced water is re-injected, then the volume of supplemental water required will be roughly equal to the volume of oil produced – and as noted, that generally need not be fresh water.

Any water used in pressure maintenance, waterflood or EOR will acquire the characteristics of produced water and will need to be reused, disposed of in disposal wells, or require substantial treatment before it is released. Therefore, it is a reasonable approximation to treat all freshwater withdrawals for oil production as resulting in consumption, i.e. the freshwater consumption and withdrawal intensities are approximately the same. The amount of fresh water consumed will depend primarily on two factors:

- 1 How much oil and produced water is drawn from the reservoir.
- 2 What fraction of the re-injected water is fresh water.

An illustrative example of freshwater consumption is shown in Figure 2.7, where possible choices about replacement and reuse result in injection water that is 8.33% (1/12) fresh, and a freshwater intensity of 0.5 barrel water per barrel oil (which equals 13.2m³/TJ).

Given the two independent variables (the amount of fresh water injected and the amount of produced water) the same water intensity can arise from many different combinations of conditions. A graphical display can be used to show the percentage of the injected water that is fresh and the displaced volume ratio, defined as

Displaced volume ratio = $\frac{\text{volume of produced water + volume of oil}}{\text{volume of oil}}$

As shown in Figure 2.8 we can use this approach to compare the differences in water consumption for different oil production operations. The graph allows the following observations to be made:

- The use of seawater and brackish water in offshore fields and the Middle East greatly reduces freshwater consumption, yielding freshwater consumption intensities close to zero barrels of water/barrel of oil.
- Using alternatives to fresh water can reduce the percentage of fresh water injected, as demonstrated by data from Texas and Canada, even as the amount of produced water per barrel of oil is increasing.
- For examples from different oil-producing regions, the freshwater consumption intensity is no more than about 1.5 barrels of water/barrel of oil, equivalent to 42m³/TJ, with significant production at intensities a factor of 10 or more lower.

Figure 2.7

Schematic flow diagram for an example of waterflood with a displaced volume ratio of six barrels of water (blue) injected into the reservoir for every one barrel of oil (black) produced. In this example, the injection water is made up of five barrels of returned produced water, 0.5 barrels of non-fresh water and 0.5 barrels of fresh water, giving a freshwater intensity of 0.5 barrels fresh water/barrel of oil produced (13.92m³/T) (not to scale).



A 2005 study estimated that globally, three barrels of water were produced with each barrel of oil^[8], i.e. a displaced volume ratio of four. Using this figure, and extrapolating estimates gained from Figure 2.8 to entire regions, allows an estimate of the displaced volume ratio for the rest of the world production, some 34% of the total, at 1.9 (0.9 barrels of produced water with each barrel of oil).

The fraction of that volume replaced by fresh water isn't known, so a worst-case scenario is offered in which the 1.9 barrels of displaced fluid in onshore fields is replaced by fresh water, i.e. a freshwater intensity of $52m^3/TJ$. This high scenario, when combined with estimates from the other 66% of global oil production, as shown in Table 2.1, results in an extrapolated value for the world average freshwater intensity for onshore conventional oil production of around $21m^3/TJ$. This is about three-quarters of a barrel of freshwater per barrel of crude oil produced. Including offshore production, which is about 30% of the world total, the water intensity overall average is about $15m^3/TJ$.

Figure 2.8

Freshwater consumption in conventional oil production for different regions and at different stages of field maturity. The horizontal axis shows the ratio of total displaced volume (oil plus water) to oil produced. The vertical axis shows the percentage of the injection water that is fresh. The solid curved lines show representative values of constant freshwater intensity ranging from 2.8m³/TJ to 139m³/TJ. The point on the 0.5bbl (barrel) curve at displaced volume ratio of six corresponds to the example in Figure 2.7. The solid symbols show reported field conditions for the UAE, Saudi Arabia, Kuwait, Oman^[8], offshore operations from Norway^[10], Lukoil^[11], and the evolution of conditions over time for Canada^[9] and Texas^[12].



Table 2.1	Oil production region	Share of production	Estimated displaced volume ratio	Freshwater consumption intensity estimated based on Figure 2.8 (m ³ /TJ)
Extrapolation of regional displaced volume ratio and	North America	17.3%	11	
freshwater consumption	onshore	14.9%		~20
intensity to world oil production.	offshore	2.4%		<1
	Eurasia	16.2%	5	
	onshore	15.0%		~26
	offshore	1.2%		<1
	Middle East	32.4%	2	
	onshore	25.8%		<1
	offshore	6.6%		<1
	Rest of the world	34.1%	1.9	
	onshore	14.3%		< 52
	offshore	19.8%		<1
	Average		4	~15
	Average onshore			~21

Unconventional oil - oil in hard-to-recover deposits

The term 'unconventional' oil can refer to difficult liquid hydrocarbons within good (high permeability) rock formations (heavy oil and oil sands), difficult hydrocarbons within difficult rock formations (oil shales), or good hydrocarbons within difficult rock formations (tight oil or shale oil).

To exploit unconventional oil, production techniques different from those used for conventional oil and reservoir rock are needed. These are described qualitatively in the following sub-sections, and the quantitative water issues are presented in the volumes of water sub-section.

Figure 2.10

Conventional and unconventional daily oil production in millions of barrels/day (mmb/d) and percentages of total production (2011 data^[7]). The total 72.4mmb/d does not include natural gas liquids (NGLs), which in 2011 totalled approximately 12mmb/d.



Figure 2.9

Schematic illustration of unconventional oil extraction facilities.

From left to right: Oil sands extraction by steam assisted gravity drainage (SAGD). Oil sands mining in an open pit and a processing facility where bitumen is separated from the sand; heavy oil extraction using steam or (less commonly) diluent, a fluid that lowers the viscosity of the bitumen. Tight oil or shale oil extraction are not illustrated here.

(This illustration is not to scale and is purely representational.)



Heavy oil

The definition varies, but heavy (high density) oil generally will not flow readily at room temperature, as it has a viscosity similar to treacle or molasses (see Figure 4.2, API gravity scale, in the refining chapter). The term 'extra heavy' is used to describe the most viscous liquid fraction. The largest reserves are in North and South America, most notably in Venezuela where the Faja del Orinoco deposit, claimed to be the world's largest, contains an estimated 1.3 trillion barrels, or 186 billion m^{3 [13]}. Heavy oils are found in similar reservoir rocks to conventional oils, occupying pore spaces between mineral grains, and can lie at any depth in petroliferous sedimentary basins.

Oil sands (also known as tar sands)

Oil sands are mixtures of bitumen, sand, water and clay, with the proportion of bitumen ranging from 1% to 18% by weight. Bitumen can be denser than water and is more viscous than heavy oil. Typically, oil sands are soft, uncemented and can be crumbled in the hand. The largest deposits of oil sands are found in Canada, Kazakhstan and Russia.

Tight oil

The term tight oil refers to oil that is trapped in fine-grain sedimentary rocks with extremely low permeability. Hydraulic fracturing may be used to produce this oil in processes similar to those used for shale gas. Because tight oil or shale oil operations are just developing, there is little information on water withdrawal or consumption. Many of the issues are similar to those for shale gas, which is discussed later in this chapter.

Oil shales

A term used to describe a range of sedimentary rocks that contain organic-rich solids called kerogens. Deposits are found worldwide, can be regionally extensive (covering tens of thousands of square kilometres) and hundreds of metres thick. There are proven processes for extracting oil from mined oil shales. In situ conversion of the kerogens in oil shales to oil for liquid extraction is still at the development stage.

Extraction processes and water

The processes involved in producing oil in a usable form from unconventional sources vary depending on the deposit type, but all involve water.

Extraction using wells

- heavy oil, oil sands and tight oil or shale oil

Unconventional oil extraction technologies are broadly divided into two main groups: cold production and thermal production.

1 Cold production technologies are used primarily for heavy oil and tight oil or shale oil. They include the use of horizontal wells with lateral branches, and pressure maintenance using water with special chemicals to increase viscosity. Hydraulic fracturing can also be used to improve the connectivity of the reservoir to production wells, particularly in low-permeability reservoirs. Another cold production technique for heavy oil, used in reservoirs of unconsolidated sand, is known as CHOPS or cold heavy oil production with sand. Powerful pumps are installed in wells to drop the downhole pressure significantly below natural reservoir pressure. This causes both sand and oil to flow into the well and then be produced at the surface.

2 Thermal production is used to exploit heavy oil and oil sands. Heat is used to reduce the viscosity of the oil in situ, allowing it to flow and be recovered. Most of these technologies involve injecting steam into the reservoir. Simple techniques rely on flooding the reservoir through injection wells, lowering the viscosity of oil and recovering it through other vertical wells. Other techniques include cyclic steam stimulation (CSS), also known as 'huff and puff', that alternates phases of steam injection with phases when oil is recovered through the same well, and steam assisted gravity drainage (SAGD), in which steam is injected along horizontal wells causing oil to drain to a second set of deeper horizontal wells (see Figure 2.11). Some operators combine elements of both CSS and SAGD in multi-scheme techniques.

The water condensed from the injected steam is produced along with the oil, together with water that already existed in the reservoir.

V Figure 2.11

Schematic flow diagram for water use in steam assisted gravity drainage (SAGD) (not to scale).

Steam generated at the surface is injected into the upper horizontal well within the oil sand reservoir. The bitumen is collected in a lower horizontal well, and pumped to a separator at the surface. The bitumen is exported and the water pumped through a heat-recovery unit to a water treatment plant for subsequent recycling or disposal. While many wellheads are typically located together, only one is shown here for clarity of illustration. 'Make-up' water enters the water treatment plant from surface or groundwater sources, which could be brackish.



Extraction by surface mining – oil sands and oil shales

For oil sands at shallow depths, down to about 70 metres, surface mining may be used, with sands excavated in large-scale truck and shovel operations. In the oil sands of Alberta, Canada, which are the bestknown deposits, some 20% of the reserves are close enough to the surface to be mined in this way^[14]. The sand is taken to a cleaning facility, where it is mixed with a hot aqueous solution containing a caustic wetting agent, such as sodium hydroxide or sodium carbonate. A flotation process is then used to separate the bitumen. Water is also used for cooling mining equipment, cleaning sand and suppressing dust.

Oil shales can be mined and processed, typically by heating in an airtight vessel. The reaction products are collected by condensation in a process commonly called retorting. The kerogen in oil shale is solid and the rock needs heating to between 350°C and 400°C to release the hydrocarbons in liquid form. This is then separated and processed to produce oil suitable for refining. Water is required for processing and cooling. Oil-shale production has a significant history, and is still used in some areas where considerations other than economics (e.g. energy security) are drivers.

Water quality required for process

• For production using wells – heavy oil, oil sands and tight oil or shale oil

Water quality for cold production techniques is similar to that for conventional oil. Thermal methods relying on steam injection require relatively pure water for the boilers. Hard or salty water requires water treatment before feeding it to boilers. The injected steam is recovered with the oil and, following heat recovery, it can be treated and recycled through the boiler.

• For mining operations – oil sands and oil shales Water used to extract bitumen from mined sand must also be purified, both on first use and on reuse, before feeding it to the boilers. Surface retorting of oil shales has similar water-quality issues to those for mined oil sands.

Wastewater and treatment before discharge

• Treatment for wells production – heavy oil, oil sands and tight oil or shale oil

Water arriving at the wellheads, in both cold and thermal techniques, will vary greatly in terms of its chemistry. Typical disposal methods for produced water are described in the introduction and conventional oil sections of this chapter. Produced water can be physically and chemically treated to yield water suitable for reuse in production. • Treatment for mining – oil sands and oil shales When oil sands are mined and processed, the resulting wastewater contains sands, silt, clay and residual bitumen, and is typically sent to tailings ponds to settle. The residual bitumen rises to the surface of the ponds where it is skimmed off. It is harmful to aquatic birds, however, so efforts are required to deter birds from landing on tailings ponds.

For oil shales, some steps in the process actually generate water, with water being an inherent by-product of oil-shale retorting. Such water contains a variety of organic and inorganic components, and requires treatment before it can be reused or discharged.

During reclamation of mine sites, water is needed to cool, compact and stabilize waste piles and to revegetate disturbed surfaces.

Volumes of water

The volumes of water required in unconventional oil production vary widely depending on the resource type, the reservoir and the technologies used for extraction and processing. Various reports on water volumes are summarized in Tables 2.2 and 2.3.

Heavy oil

The amount of fresh water used in thermal techniques depends on the ability to substitute saline water sources, the reservoir characteristics and the efficiency of recycling. For example, at the Californian Kern River heavy oil field where steam is injected, 143,000m³/day of water^[13] are used, giving an average water-to-oil ratio of 9:1. Around 50% of this water is reused, with the remainder treated and blended with other freshwater sources for crop irrigation^[13]. The water consumption is 4.5bbl/bbl of oil, resulting in a freshwater intensity of 135m³/TJ^[13].

Oil sands

Freshwater use in oil sands extraction has declined, mainly due to increasing recycling rates and the use of treated brackish or saline water for in situ recovery. The Canadian Association of Petroleum Producers reported in 2012 that recycling and reuse averaged 90% in the oil sand operations of Alberta^[15]. The operators of the oil sand field at Cold Lake in Alberta, Canada, report using less than 0.5m³ of fresh 'make-up' water per m³ of oil, with up to 95% of the water injected as steam now being recycled.

Following extraction, the bitumen recovered must be treated to reduce its viscosity so that it can be transported as a liquid. Bitumen produced can be refined (chemically modified using thermochemical methods) to generate sweet synthetic crude oil. This process is called upgrading, and it requires both cooling water and process water. Alternatively, bitumen can be diluted with light liquid hydrocarbons so it can be transported to distant refineries^[16].

Table 2.2

Water consumption intensities reported for oil sand production and upgrading. Water consumption is shown as an intensity in m³/TJ and as a ratio in unit volume per volume of upgraded bitumen product (bbl/bbl). Consumption is shown for both mining and in situ production. Most reports do not specify requirements on water quality, or the fraction of the consumed water that was withdrawn from freshwater sources.

Oil sands						
Location/report	Туре	Water consumption intensity m ³ /TJ	Water consumption ratio bbl/bbl	Water ratio reported for upgrading		
Alberta, Canadian Association	Mining	93	3.1			
of Petroleum Producers (2010) [15]	In situ	12	0.4			
Alberta, Pembina Institute (2010) ^[17]	Mining	87	2.9	Upgrading: 0.8bbl of water/bbl of bitumen		
	In situ	57	1.9	reported for upgrading		
Canadian Athabasca Oil Sands, Shell (2011) ^[18]	Mining	75	2.5	Upgrading: 0.4bbl of water/bbl of bitumen. Both SAGD and cold recovery operations		
	In situ	60-78	2-2.6			
Argonne National Lab	Mining	120	4	Upgrading: less than one gallon of water/		
Data Review (2009) [19]	In situ	39 (SAGD) 66 (CSS) 150 (multi-scheme)	1.3 (SAGD) 2.2 (CSS) 5 (multi-scheme)	gallon of crude (Peachey 2005)		

Note: calorific value of upgraded bitumen (synthetic crude oil) was assumed equal to 38MJ/kg.

Tight oil

Field data on the levels of water withdrawal and consumption for tight oil or shale oil are not readily available, as exploitation is in its early stages. The International Energy Agency^[7] reports a range of $5-100m^3/TJ$. Because the hydraulic fracturing operations used for tight oil or shale oil are derived from those used for shale gas, the techniques and volumes described in the unconventional gas section can be used as a point of reference; however, the recovery factors are uncertain.

Oil shale

There is a history of oil-shale mining, but limited operational information on water use. The levels of water consumption are presented for pilot-scale and engineering studies in Table 2.3.

The oil shale has to be treated to release the oil and this requires water, as does the upgrading process for conversion into synthetic crude.

Table 2.3

Water consumption intensities reported for studies of oil-shale production. Water consumption is shown as an intensity in m³/TJ and as a ratio in unit volume per volume of product (bbl/bbl). Assessments of consumption are shown for both mining and in situ production. Most reports do not specify requirements on water quality or the fraction of the consumed water that was withdrawn from freshwater sources.

Uil shale					
Location/report	Туре	Water consumption intensity m ³ /TJ	Water consumption ratio bbl/bbl		
RAND report on oil shale development in US (2005) ^[20]	Mining	26 - 136	0.9-4.5		
Colorado, Utah and Wyoming, DOE Fact Sheet (2006) ^[21]	Mining	ning 78 – 120			
	In situ	30 - 90	1-3		
Green River Formation in Colorado, Utah, and Wyoming, Carnegie Mellon	Mining	207	7		
University Data Review (2009) ^[22]	In situ	125	4.2		
US Government Accountability Office (2010) ^[23]	Mining	54– 93 Average 75	1.8 – 3.1 Average 2.5		
	In situ	21 – 252 Average 99	0.7 – 8.4 Average 3.3		

Note: calorific value of upgraded bitumen (synthetic crude oil) was assumed equal to 38MJ/kg.

Conventional gas - a prime energy source for power generation

Although well known to the ancients as the source of eternal flames in the Middle East and Central Asia, natural gas was of limited use until pipelines could be produced economically. Distribution is still a barrier to gas use, but massive gas pipeline networks have been built in some countries. In addition, long-distance transport has been enabled by the advent of liquefied natural gas (LNG), as a means of transporting large volumes across oceans.

Natural gas composition and energy content

Natural gas is found in the subsurface both in gas reservoirs and in combination with oil reservoirs. As extracted, it is a mixture of hydrocarbon gases, primarily methane (70 - 90%) with up to 20% of ethane, propane and butane. Common impurities present in the produced gas are carbon dioxide, nitrogen and hydrogen sulphide.

Amounts of natural gas are measured in normal cubic metres (for gas at 0°C at 101.325kPa) or in standard cubic metres (for gas at 16°C and 101.56kpa). When purified for commercial use, natural gas can be almost pure methane, which sets the upper limit for the thermal energy content as 55MJ/kg. World production of natural gas in 2011 was 3,283 billion cubic metres = 2,955 million toe = 123 million TJ ^[3,7,24].

Hydrocarbon reservoirs in which gas is the dominant hydrocarbon, and which can be developed and produced based on the natural flow of gas through reservoir rocks, are termed conventional gas.

Extraction processes and water

Gas is naturally under pressure within the reservoir, and when a well initially produces from a gas-bearing rock formation, the gas will spontaneously expand and flow into the wellbore and then to the surface. In conventional reservoirs the gas can easily flow through the reservoir-rock pore spaces towards the wellbore.

Produced water, treatment and disposal

Natural gas arriving at the surface will contain water vapour, which when condensed is the main source of produced water in conventional gas fields. The volumes of condensed produced water are small in comparison with oil-field produced water, but may contain aromatic hydrocarbons, including benzene and toluene. A few gas fields produce significant volumes of water, which is mostly disposed of by injection into disposal wells.

Volumes of water

Because water injection is not used in conventional natural gas production, the water consumed in drilling may be the primary factor in water use. The resulting water intensity will depend on how many times the mud is reused in different wells and the lifetime production of each well. A typical US well production value is 1,550 million cubic feet (44 million m³ or approximately 1,700TJ)^[25]. A typical value of water consumption per well is reported as 85 - 116 thousand gallons $(320 - 441m^3)$ ^[25], yielding a water consumption intensity significantly less than $1m^3/TJ$, even if the drilling mud is not reused in other wells.

Gas processing

Before gas can be introduced into distribution pipelines, it has to be processed to meet the operating specifications, including energy content per unit volume, at the point of use.

Processing plants

In a typical production field, water and heavier hydrocarbons that condense at surface temperature are removed, either in simple gravity separators, or by glycol-based dehydrators. Further dehydrators at the processing plant are employed to reduce the water content to around 120 parts per million (ppm), well below the typical wellhead level of 800 – 1200ppm^[26].

After dewatering, CO_2 and hydrogen sulphide (H₂S) must be removed to prevent corrosion of pipelines. The dried, purified hydrocarbon gas then passes to a process plant where the different hydrocarbon fractions present are separated for export.

Water use in natural gas processing

The chemicals, typically amines, used to separate CO_2 and H_2S are often concentrated aqueous solutions. Water is required to cool the separation towers and other machinery, especially compressors, and to provide steam, which is used to regenerate the amine by driving off the carbon dioxide. Cooling water can be of low quality (see power generation chapter) but steam generation requires water with low salinity to avoid scaling.

Volumes of water

Water use in natural gas processing is mostly associated with make-up of the amine solutions, but around 15% of that make-up can be sourced from water recovered in the gas dehydration process^[27]. Fresh or desalinated water is used to feed the boilers that produce steam for amine regeneration^[28].

Water consumption intensity for gas processing ranges from around 0.1 to $0.6m^3/TJ^{[27,29-32]}$. If the gas contains sulphur, however, and the sulphur recovery unit is included, the overall water intensity increases because the processes use heat and thus need cooling water^[33].

Unconventional gas - a new and growing resource

The term 'unconventional gas' describes natural gas deposits found in low-permeability reservoirs that cannot be exploited economically by conventional means. The term changes through time and the definition in this book includes gas contained in tight reservoirs and shales, as well as coalbed methane.

Tight gas

The permeability in a tight gas reservoir rock is less than 0.1 millidarcy (mD). This is a factor of 10 to thousands of times less permeable than conventional natural gas reservoirs. The use, however, of hydraulic fracturing techniques to create flow paths can result in an economically viable field. For example, the tight gas reservoirs currently exploited in Wyoming, US, have porosities of 12% but permeabilities of only 0.1 millidarcy.

Shale gas

Shales – fine-grain sedimentary rocks – have even lower permeability than tight gas reservoirs, typically a few tenths of a microdarcy, which does not allow gas to flow economically into conventional wells. Shales can, in places, be hydraulically fractured to produce large quantities of natural gas.

Coalbed methane (CBM)

Coals are riven with a multitude of minute fractures called cleats that, combined with their pore system, give them an extraordinarily large surface-area-to-volume ratio. Coal possesses the property of adsorbing methane on to its surface; most coal seams contain trapped methane. Recovery is hampered by the tight retention of the gas in the coal.

Figure 2.12

Conventional and unconventional annual natural gas production in billions of cubic metres (bcm) and percentages of total production for 2010^[34]. More recently, the proportion of gas supplied from unconventional sources is increasing, although conventional gas still remains the majority source.



Figure 2.13

Schematic illustration of unconventional natural gas extraction facilities.

From left to right: shale gas production using hydraulic fracturing from a horizontal well; tight gas production from a sandstone reservoir using fracturing from vertical wells; coalbed methane (CBM) production using a vertical well to dewater the coal seam; and a deep injection well for water disposal. (This illustration is not to scale and is purely representational.)



Figure 2.14

Schematic flow diagrams of water use in unconventional natural gas production in shales and coal seams (not to scale).

Diagram (a): the shale is fractured hydraulically using water-based fluid injected into a horizontal well. Gas is subsequently produced along the same well path. The fluids pass through a separator when they reach the surface. The fracturing fluid and any water from the reservoir are treated for recycling, exported for use in other fracturing jobs or disposed of. The disposal is illustrated with an injection well, which is shown close to the treatment plant for illustrative simplicity.

Diagram (b): the coal seam is dewatered using pumps. At the surface, water present in the gas is removed in the separator before the gas is piped to export and the water disposed of by injection into a non-potable aquifer. The disposal is illustrated with an injection well, which is shown close to the production site for illustrative simplicity.



Extraction processes and water

Hydraulic fracturing

During its development and early application, fracturing used predominantly fresh water because the chemical additives used were sensitive to saltwater. This requirement is changing as a result of industry effort to understand the fundamental science needed to develop alternative chemicals. As a result, to reduce the freshwater withdrawal and consumption for fracturing, there is the possibility to use brackish water or seawater, and recycled water that has been recovered after a fracturing operation (e.g. the flowback water).

The proportion of brackish water being used as a substitute for fresh water is not well documented. Data available^[35] for Texas shows that the proportion of brackish water used for fracturing in 2011 was between 0% in the East Texas basin, to 80% in the Permian Far West basin. Reuse of flowback water ranged from 0% to 20% of the total water used for hydraulic fracturing ^[36]. Regulation, fresh water constraints and the economics of water treatment will determine whether brackish water is used instead of fresh water.

Extracting coalbed methane

The larger pore spaces and fractures in coal seams are often filled with water and, to free the methane trapped in the coal, a well is drilled into the seam and the coal around the wellbore dewatered if required. Over time, as the water saturation around the well decreases, some of the methane becomes mobile and flows into the wellbore. Down-hole pumps are used to dewater the coal seam and keep the water out of the wellbore. Hydraulic fracturing of coal seams can improve gas production rates by increasing the coal volume connected to the well.

Gas

export

Separator

Disposal well

Coal seam In-seam water

Effect of processes on water and treatment before discharge

The water used in hydraulic fracturing, connate water associated with tight and shale gas, and water extracted in dewatering coal seams all carry different types of contaminants.

The chemistry of water produced with tight and shale gas depends on the fracturing fluids and the impurities from the reservoir, and varies greatly among different shale locations. The produced water cannot be allowed to enter the water catchment area or any freshwater aquifer.

A well-engineered wellbore, using standard practices, will isolate any shallow aquifers. Disposal methods, for returned fluid that cannot be recycled, include injection into specially drilled disposal wells that penetrate permeable formations that are isolated from freshwater aquifers.

Once a well is fracture-stimulated, any production of connate water is mixed with return of much of the original fracturing water. Though the connate water from tight gas reservoirs is similar in composition to that from conventional gas fields, the produced water of course will also contain the fracturing chemicals.

Water pumped from coal-bearing strata to promote coalbed methane production can have a high saline content. Present best practice is to dispose of the majority of water in injection wells engineered to ensure that saline water does not flow into drinking water aquifers.

Volumes of water

Calculating water intensities for shale gas and tight gas is subject to significant uncertainties, as the demand for water for fracturing occurs at the beginning of operations, whereas the full energy content delivered from the well will only be known following years of production. Until more operational information is available, the water intensity is estimated using the estimated ultimate recovery for wells.

Large quantities of water are required to initiate production by hydraulic fracturing. Treatments for tight gas range from approximately 225m³ of fracturing fluid, to the largest treatments exceeding 3,800m³ of fluid. Shale fracturing treatments range from approximately 11,000 to 35,000m³ of fluid^[37] and depend on the type of fluid system used. There is some progress in decreasing freshwater consumption through increased use of brackish water and increased recycling of produced water. Data from Texas shows that the amount of fresh water can be as low as 20% of the total but is more often higher, ranging up to 95%^[36]. The water intensity decreases when the estimated natural gas ultimate recovery is higher, as shown in the analysis^[36, 38] of 400 wells in the Barnett shale, in the US, in Figure 2.15. While the mean lifetime intensity is about $6m^3/TJ$, the range is from approximately 3 to $17m^3/TJ$, reflecting significant well-to-well variation^[36]. These align closely to data from a study^[39] for Texas showing freshwater consumption of approximately $10m^3/TJ$ for fracturing shale gas wells. Table 2.4 illustrates the estimated mean, low, median and high values of water-use intensity in the three largest contemporary shale gas plays in the US. By contrast, for tight gas, one source^[34] reports water-use intensities between 0.1 and $1m^3/TJ$.

Figure 2.15

Scatter plot of water intensity in m³/TJ against esimated ultimate recovery in millions of m³ for 400 horizontal hydraulically fractured wells in the Barnett shale within Tarrant and Johnson Counties, Texas, US. This shows the variability in water intensity and the trend for lower lifecycle water intensity for wells with higher estimated ultimate recovery volumes of natural gas. The quantity shown is total water intensity, not freshwater consumption intensity, which will depend on the proportions of brackish water or reuse.^[36]



Table 2.4

Estimated ranges for the water intensity of natural gas production from the three largest shale locations in the US, based on the typical volume of water used in hydraulic fracturing treatments in each play, and per-well estimated ultimate recovery (EUR). The percentile values, P10, P50 and P90, reflect the range in water intensity caused by the considerable variability in well productivity within shale plays. Ninety per cent of all wells have a higher water intensity than the value in the P90 (low value) column; similarly 50% for the P50 column and only 10% for the P10 (high value) column.

Water-use intensity m ³ /TJ ^[39-41]				Estimated water use per well for fracturing m ^{3 [36]}	Estimated water use per well for drilling m ^{3 [36]}	
	Average	P90 (low value)	P50 (median)	P10 (high value)		
Barnett	6.6	3.7	7.6	16.5	11,000	1,500
Haynesville	5.9	3.6	6.3	11.9	22,000	3,800
Marcellus	5.7	2.9	6.6	16.6	16,000	300

Note: calculation method^[36] based on 2010 data and peak-month production data, as provided by the Drilling Info HPDI Database, 7 March 2013.

Estimated ultimate recovery assumes wells produce for 30 years or until production falls to zero, whichever occurs first.

Water intensity calculations include water use for drilling along with well stimulation.

Coal - the dominant fuel for world electricity production

By the mid-19th century, coal mining was the largest organized industry on earth, with millions of miners in Europe alone. Such was the scale of the industry that, in 1865, the economist William Stanley Jevons raised the question of coal running out.

Today, the fuel that powered the industrial revolution remains our most exploited energy source. Coal provides some 30% of the world's primary energy use, mainly for electricity generation, and is vital to the iron and steel industry, which consumes around 12% of annual coal production^[42].

Figure 2.16

Schematic illustration of coal mining. From left to right: underground production using shafts; open pit with spoil heaps awaiting reclamation.

(This illustration is not to scale and is purely representational.)



Coal composition and energy content

Coal is a combustible sedimentary mineral composed mainly of carbon but also containing hydrogen, oxygen, nitrogen and sulphur. Depending on the organic maturity over the millions of years of its formation, coal can be found in different forms and with different energy contents. The moisture and energy content of coal define its application, with low-energy, high-moisture lignite used for heating, and high-energy, low-moisture bituminous coals used for steel manufacturing. Typical ranges of energy content for different coal types are:

Hard bituminous (black coal)	> 23.9MJ/kg
Sub-bituminous coal	17.4 – 23.9MJ/kg
Lignite (brown coal)	< 17.4MJ/kg

In 2011 a total of 7,783 million tonnes (Mt) of coal was produced worldwide (= 3,955.5 million tonnes oil equivalent = 165 million TJ = 165EJ), which was used in producing about 40% of the world's electricity and about 70% of the world's steel $^{[7, 14, 43]}$.

Extraction

Water is used in mines for dust suppression and machine cooling, but the dominant water use is in coal preparation (also called coal washing or coal beneficiation) (see Figure 2.17). Dust is a particular hazard in coal mines, as coal dust can be explosive. Also, both coal dust and silica-rich dust from cutting rocks must be suppressed, as it can otherwise accumulate in the lungs of miners, leading to debilitating respiratory disease.

In addition to the need to source water, mining engineers also have to cope with water that they encounter during the mining process along with water from rainfall. The produced water in coal mines often contains sulphuric acid and iron as well as being saline. Depending on the setting, withdrawn and consumed water volumes can easily be exceeded by the volumes of produced water.

If the produced water, which contains suspended coal particles, is not recycled for mining processes, it must be treated before discharge. Treatment may include desalination, removal of suspended solids and the addition of alkali to counter acidity; but, historically in many mines, wastewater has been collected behind tailings dams and simply left to evaporate.

Coal treatment

Coal leaving a mechanized mine contains rock that formed part of the seam, rock that was mined along with the coal, and sulphur-bearing minerals. Impurities can be removed on site in a process known as beneficiation or coal preparation. This reduces transport costs, increases the bulk calorific value and lowers the ash and pollutant concentration, especially sulphur. Beneficiation relies mainly on 'washing the coal', for instance using water with magnetite in suspension, in a cyclone. The waste products are taken to tailings ponds where the fluids are separated and either recycled, evaporated or treated before discharge.

Dry techniques also exist to separate the higher- density waste from the lower-density coal and these are increasingly being introduced in areas of water stress and at mines with extremely low temperatures. Arguments against dry treatment include health risks to operators and the risk of fire and explosion^[44].

Figure 2.17

Schematic flow diagram of water use in coal extraction and washing (not to scale).

From left to right: open-pit mining showing extraction of produced and rain water, and supply of water for dust suppression; similar process for an underground mine; on the surface, a plant treats water from the mines and combines with external water sources to supply mine and coal washing plant needs. The plant also treats water from the mines before recycling or disposal.



Volumes of water

The amount of fresh water withdrawn depends on local regulation and physical availability. The following factors determine how much freshwater is withdrawn:

- Alternative sources and recycling non-fresh water such as water entering mines or water recycled from operations can be used for some mine operations.
- Coal washing decisions around the type and degree of coal preparation.
- Nature of the coal seam this will affect the amount of water required for dust suppression and machine cooling.
- Mine location in water-stressed areas, evaporation rates from stored water can dominate consumption and make it economically viable to cover or deepen reservoirs. In more temperate climates, like the Appalachians in eastern North America, where rainfall exceeds evaporation rates, well-run mines may not need to draw on any external water sources.

Water issues in hot or arid climates are illustrated in Table 2.5 for cases in China and the Bowen Basin in Australia. In China, 70% of coal mines are located in water-scarce regions, and 40% of them have severe water shortage problems, especially those in northern China^[45]. The Bowen Basin, by contrast, is located in a tropical to subtropical climate zone, with dry winters and hot summers, sometimes with heavy precipitation.

The results in Table 2.5 fall within the typical reported ranges of freshwater consumption for coal mining. For instance, the 2006 US Department of Energy's Report to Congress^[46] used Gleick's (1994)^[47] estimates for the water consumed by coal mining as $3 - 20m^3$ of water per TJ of energy in the coal, depending on the source of the coal and with an additional $4m^3$ per TJ used for coal washing. Other results from engineering studies and tabulations yield similar estimates ^[48–50].

Table 2.5

Freshwater consumption intensities reported for coal production in China and Australia's Bowen Basin. Water consumption is shown as an intensity in m³/TJ and as a ratio in m³/tonne. The results come from both surface and underground mining.

Freshwater consumption numbers						
	Location/report	m ³ /tonne	m ³ /TJ	Process	Notes	
China ^[45]	Shanxi Province	0.25 - 0.30	9.40 - 11.28	Underground mining	About 22% of Chinese operations reuse mine water, and about 43% of the coal is washed.	
	China average	0.06 – 1.6	2.3-61	95% underground mining		
		0-0.2	0-7.52	Dry-wet coal preparation		
Australia ^[51]	Bowen Basin coal mines	0*	0*	Surface mining*	The freshwater use represents	
		0.15	5.54	Mixed surface and underground mining	15 – 49% of the total water use among seven different mines and includes rainwater	
		0.13	5.06	Underground mining	captured on the site.	
		0.15	5.61	Coal preparation		

Note: conversion assumption one tonne of coal = 26.6GJ.

* Freshwater consumption in this example is zero because the source is non-fresh.
Uranium - the source of 13%^[1] of the world's electricity

In 1956 the world's first commercial nuclear power plant opened in north-west England, less than 60 years after French scientist, Henri Becquerel, discovered that uranium salts could blacken photographic plates, even when they were wrapped in paper.

Uranium is a fairly common element in the earth's crust, never found as a pure metal, but instead as a range of minerals. Uranium minerals are concentrated within veins and a wide variety of other deposit types. Countries with major deposits include Canada, Australia and Kazakhstan.

Uranium – isotopes and enrichment

Uranium is a metallic element composed of three isotopes: U-238 with 99.29% abundance, U-235 with 0.71% abundance and U-234 with 0.005% abundance. U-235 is the radioactive isotope needed for generating power in nuclear reactors. For common reactors using low-enriched uranium (LEU), the fraction of this isotope has to be increased to 3 – 5% in a process called enrichment. In 2010 the 63,875 tonnes of newly mined uranium was used in generating 13% of world electricity.

In nature, uranium is commonly found as uranium oxides, with the dominant compound U_3O_8 . Mined uranium ore can have a concentration of 0.02% to 20% of uranium oxide, which needs to be upgraded to around 80% to be used in the enrichment process^[2, 52-53].

Figure 2.18

Schematic illustration of uranium mining, both underground and surface. From left to right: open-pit mining; in situ leaching (ISL) with injection and production wells; and underground mining from shafts.

(This illustration is not to scale and is purely representational.)



Figure 2.19

Uranium extraction by mining type. The slice labelled 'Other' comprises co-product and by-product uranium recovered at gold and copper mines (2010)^[2].



Before uranium can be used as a fuel in nuclear reactors, the ore has to be mined and milled. The uranium salts are then converted into a useable form, enriched in U^{235} and formed into packages to suit the reactor type.

Extraction

The method of uranium mining varies widely, reflecting the variety of deposit type, as shown in Figure 2.18. Conventional open-pit and underground mines have been joined, since 1974^[52], by in situ leaching (ISL), which now accounts for some 39% of production^[2].

Uranium mining is illustrated schematically in Figure 2.20(a) for the case of an open-pit operation. As with conventional mining, water use is dominated by dust suppression. Dust is particularly hazardous in uranium mines, as particulates entering miners' lungs have the potential to emit radiation.

ISL can only be used in deposits where the mineral is in porous and permeable rocks, in a confined aquifer. Oxidizing and complexing agents are pumped down injection wells, as shown in Figure 2.20(b) on the next page, to form a solution with the groundwater that is present. The solution dissolves the uranium minerals and is then recovered through production wells. At the surface, the uranium is removed from the solution, which is then re-injected to recover more uranium.

Groundwater from the uranium-bearing aquifer is used to form the bulk of the leach solution circulating through the ore body. ISL can only be undertaken in deposits where this groundwater is isolated from any aquifer used for other purposes. In ISL mines, small volumes of leachate are removed to ensure that there is always a net inflow of water towards the operation, so stopping the solution moving into other formations. There is often a greater volume of mine drainage water than water introduced into the operation.

Figure 2.20

Schematic flow diagram of water use in uranium extraction, processing, conversion, enrichment and fuel fabrication (not to scale).

Diagram (a): open-pit operation with water supplied for cooling, dust suppression and milling; treatment plant processing water from the open pit and the mill; with disposal illustrated as by evaporation.

Diagram (b): in situ leaching (ISL) operation with water-based leachate supplied to the ore body; returned leachate containing the mineral processed at surface; with excess water disposal illustrated as by evaporation.

Diagram (c): shows three major process steps for conversion, enrichment and fuel fabrication. Water of a high quality is required within conversion and fabrication, with lower-quality water needed for cooling in conversion and enrichment.



c Conversion, enrichment and fuel fabrication



Ore processing

For conventionally mined uranium, the ore is first crushed and then ground in large water-filled mills before being leached in acid or alkaline solution. After leaching, the spent material (tailings) can be pumped into old mine workings, if space exists. More frequently it is pumped into tailings ponds. In some mines, uranium is extracted by a process known as 'heap leaching' in which crushed ore is piled into large heaps that are sprayed for months with recirculated leaching agents. The resulting leachates, from both milling and heap leaching, are passed through ion exchange units to separate out the uranium content, which is precipitated as a concentrate of the uranium oxide U_3O_{8r} historically known as yellowcake.

At in situ leaching mines, the separation process circumvents the milling needed for mined ores. The majority (97 – 99%) of the fluid pumped to the surface is normally recycled in continuous ISL cycles after the uranium in the fluid is captured by ion exchange.

Conversion and enrichment

As illustrated in Figure 2.20(c) on the previous page, to manufacture fuel, U_3O_8 has to first be converted into uranium hexafluoride (UF₆) to allow U^{235} to be enriched from an average of 0.7% to the 3 – 5% concentration required in most commercial reactors. Conversion requires chemical processes, the most common of which uses water in the reactions and also as a coolant.

For the subsequent enrichment of the UF₆, two methods have been used: gaseous diffusion which is now being replaced by gas centrifugation. Compared with centrifugation, diffusion requires massive energy inputs, as the gas needs to be passed through membranes several thousand times and large volumes of cooling water^[54] to dissipate waste heat. The cost of energy has led to the phasing out of diffusion and the last known diffusion plant closed in May 2013. The water consumption for this process is shown in Table 2.8 and Figure 2.21 for comparison with gas centrifugation.

Nuclear fuel fabrication

In this process the enriched material is converted into ceramic pellets and inserted into rods that can be lowered into the reactor core. Water is used within the chemistry of this process. Around 2% of nuclear fuel comes from mixed oxide fuel (MOX) manufactured mostly from used reactor fuels. By using plutonium and uranium oxides, MOX has provided the means for burning weapons-grade plutonium in nuclear reactors^[52].

Water in mining, processing and enrichment

Water quality is not critical for extraction and processing, but for use in the chemical reactions at the heart of uranium conversion, enrichment and fabrication, water must be pure.

Contact with uranium minerals will pollute water: the water from the mines and processing plants must be captured and held in secure tailings ponds so that solids can settle out. The remaining liquids are then disposed of either by natural evaporation or recirculation to the milling operation. In ISL mines, any water withdrawn from the ore body is either evaporated or re-injected ^[55].

Volumes of water

Overall, in 2010, 63,875 tonnes of uranium were processed and delivered to nuclear reactors, having consumed approximately 74 million m³ of water. This resulted in the generation of 2,630TWh of electricity^[2].

The majority of the water use, about 95%, is accounted for by mining, milling and enrichment, as shown in Tables 2.7 and 2.8 and Figure 2.21. Disposal of wastewater removes water from the catchment area and therefore is considered as consumption.

The most significant consumption of water, shown in Table 2.8, arose from gaseous diffusion enrichment plants. There was significant reduction in the proportion of uranium enriched by this process (down to around 25% in 2010 from approximately 50% in 2000^[52]), and, as previously mentioned, the last known gaseous diffusion plant was closed in 2013. As a result in the future, the volumes of water consumed in conversion, enrichment and fabrication will be minute compared with those consumed in mining and milling.

For conversion and enrichment plants that use closed-loop cooling, water consumption and withdrawals are approximately equal; for plants that use once-through cooling, withdrawals are about 10 times larger than consumption.

Table 2.7

Freshwater consumption intensities reported for uranium mining and ore beneficiation. Water consumption is shown as an intensity in m^3 /tonne and in m^3/TJ_{tr} as well as total annual water consumption for the three main mining types ^[2, 56].

Mining type	ing type Portion of total uranium mined (2010) ^[2]	Freshwater consum	ption	2010 water consumption	
		m ³ /tonne natural uranium metal	m³/TJ _t *	million m ^o **	
Open pit	23%	760	1.45	9.5	
Underground	32%	1,770	3.39	31	
ISL	39%	250	0.480	5.3	

Note: percentage of uranium mined does not total 100, because 6% of today's uranium originates as by-products of non-uranium mines.

* TJ_t – terajoules of thermal energy. Different nuclear plants have different conversion efficiencies.

Here the conversion factor used for thermal energy per equivalent tonne of natural U metal (non-enriched) is 0.52TJ₁/kg uranium metal.

** Based on a total of 54,670 tonnes natural uranium mined.

The remainder of the uranium used in electricity generation in 2010 was provided from secondary sources,

such as by-products from other metal-mining operations, plus recycled nuclear materials.

Table 2.8

Freshwater consumption intensities reported for uranium conversion, enrichment and fuel fabrication processes. Water consumption is shown as an intensity in m^3 /tonne natural U and in m^3/TJ_t , as well as in annual totals for the three processes ^[2, 56].

Process	Process by type	Portion of	Water consu	mption	2010 water consumption
		type (2010) ^[2]	m ³ /tonne natural U	m ³ /TJ _t ^[56]	
Conversion	Wet process with closed loop cooling	100%	16	0.03	1.0*
Enrichment	Gaseous diffusion	~28%	1,470	2.82	25.0**
	Gas centrifuge (natural uranium)	~72%	30	0.06	1.3**
Nuclear fuel fabrication	Standard		12	0.023	0.8*
	MOX (mixed oxide fuel)		78	0.15	0.1***
			·		

* Based on total 63,875 tonnes natural uranium equivalent.

** Based on total 59,375 tonnes natural uranium equivalent. *** Based on total 1,100 tonnes natural uranium equivalent.

Figure 2.21

Comparative illustration of water consumption intensities, in m³/TJ_t, for the steps involved in uranium fuel production.



Risks, opportunities, and innovations

Although the extraction of energy materials drives only a small fraction of worldwide water withdrawals and consumption, regional issues (especially in water-scarce areas) and waste disposal remain sources of risk. Short-term risks may arise when extraction operations require a large up-front consumption of water, with hydraulic fracturing being the most obvious example.

Replacing freshwater in extraction operations with low-quality water, reused process water or produced water is a powerful opportunity for reducing freshwater consumption. Many operations, however, are sensitive to water quality, so treatment of the replacement water is needed. With improvements in existing technologies such as desalination and chemical separation, there are opportunities to reduce the cost of treatment. Innovation is also under way to find lower-cost alternatives to tailor the treatment of brackish or other lower-quality water so that it is compatible with the reservoir properties and any additives used in operations.

Recycling produced water for other uses is often uneconomical due to high salinity. In some cases, however, produced water can be treated and support local needs for water.

Chapter summary

Replacement of fresh water with low-quality water sources and reuse of produced and process water are particularly useful approaches to reducing freshwater consumption in the extractive industries. Early reports ^[47, 57] about water use for energy reflect older practices where reuse was less common, and distinctions between types of water used were not always reported. Unfortunately, most modern reports on water use for extraction unquestioningly repeat the older data, often through a string of citations of intermediate reports without any updates based on more recent data. To the extent possible, we have drawn on reports from current operations to develop updated estimates of water consumption intensities, being clear where possible about distinctions between fresh water and other water sources. Table 2.9 displays an estimate of the total amount of fresh water used in the extraction of energy minerals in 2010. Information for each energy source is drawn from material in the previous sections. Consumptive water intensities have been chosen to provide a high-end scenario for total water consumption. The total freshwater consumption resulting from this scenario is around 9km³ (9 billion m³), of which 7.68km³ was consumed in coal and conventional oil production.

Table 2.9

Estimates of consumption intensities and corresponding annual global water consumption for different primary energy sources. For each energy source, the proportion of primary energy is shown as a percentage and inTJ. The intensities are high-end estimates enabling calculation of a high-end value of the annual freshwater consumption volumes, which total 9km³. The notes indicate the data source from within the chapter.

Energy source	Share of world's p energy produced	rimary (IEA, 2010 data)	Global average consumptive water intensity	Annual freshwater consumption volume	Notes
	%	Million TJ	m³/TJ	km ³	Source
Conventional oil	30.7%	145.0	15	2.18	Figure 2.8 and Table 2.1
Unconventional oil	1.7%	8.28	100	0.83	Tables 2.2 and 2.3
Conventional natural gas	18.3%	78.6	< 1	0.08	See conventional gas, volumes of water section
Unconventional natural gas	2.6%	13.1	17	0.25	See unconventional gas, volumes of water section
Coal	27.3%	137.0	40	5.50	See coal, volumes of water section
Uranium mining and processing	5.7%	28.5	2.5	0.07	Tables 2.7 and 2.8
World		500.0		8.9	
Note: 1km ³ = one billion m ³					

As noted in the introduction, water withdrawn for one purpose, by definition, may not be readily available for other uses, hence the amount of water withdrawn can be a determinant of water stress. Therefore, it is useful to understand the volumes of water withdrawn for extraction and compare them with world total withdrawals. In oil, natural gas and coal extraction processes, water withdrawn is usually retained in the sub-surface workings or disposed of in dedicated strata. Therefore the vast majority can be considered as consumed. Indeed the majority of operators when reporting consumption assume that it equals withdrawal, as so little can be returned at an appropriate quality to the original water catchment area. The exception to this is water used for cooling, the majority of which is involved in uranium enrichment. There, water withdrawals may be 10 times larger when once-through cooling is employed. Using a pessimistic estimate of such withdrawals gives an annual worldwide withdrawal intensity for fossil fuels and uranium extraction of approximately 9.2 billion m³. This is a relatively small amount, less than half a per cent of the world water withdrawals of slightly more than 4,000 billion m³, and will be smaller in the future as gaseous diffusion is no longer used. Additional water withdrawal and consumption occurs in processing fossil fuels for end use. This is discussed in the refining section.

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- When evaluating fresh water
 withdrawal and consumption intensity
 of plants, only irrigation water is
 included because the natural process
 of evapotranspiration of rainwater is an
 essential part of the hydrological cycle.
 Changes in evapotranspiration patterns
 with changing plant cover need to
 be assessed in terms of overall
 ecosystem impacts.
- The water needed for any crop depends on how efficient the plant is at using water and on local climatic conditions; the plant species water-use efficiency normalized by the vapour pressure deficit is a measure that includes both. Comparison of this metric facilitates optimal plant choice for regionally responsible planning.
- Eighty per cent of all crops are solely rainfed; most commercial biofuel crops are grown in areas where little irrigation (2 6%) is needed. As a result biofuel crops' water consumption intensity due to irrigation is approximately 5,000m³/TJ, much lower than estimates based on global crop averages.
- In 2010 the estimated freshwater withdrawal for biofuel crops was about 20km³, corresponding to less than one per cent of global freshwater withdrawals.

3 Water in biofuel crops

Introduction

Bioenergy is a general term referring to energy derived from any renewable biological material (often referred to as biomass), such as plant matter or animal wastes. Bioenergy feedstocks, such as wood and plant waste, have historically been burned for heat and cooking fuel, and can also be burned to generate electrical power. The possibility of using liquids derived from biomass for transportation fuels has been considered since the earliest days of the automotive industry. The commercial development of this concept was demonstrated in Brazil, and its increasing use worldwide has been driven by the low-carbon footprint of biofuels as well as by concerns about energy security. Growing bioenergy crops also provides an extra source of income for farmers, and offers an economic opportunity for land that has fallen out of agricultural use.

The water intensity of biofuel crops is governed by the volume of water withdrawn from local freshwater sources and subsequently consumed in their growth.

As with food crops, the amount of water needed for irrigation is highly dependent on local conditions and type of plant. Worldwide, about 80% of cropland is rainfed^[1] (i.e. not irrigated) and provides about 60% of global crop production. The remaining ~20% of cropland, about 250Mha^[2, 3], is irrigated during at least part of the growing season and yields about 40% of all production^[4]. The dominant factor in determining where irrigation is needed is the amount of rainfall. This varies dramatically from desert regions with almost no precipitation to regions where there is more than 1,000mm of precipitation per year.

The yields of crops and the amount of irrigation needed depend on many factors in addition to the local rainfall. In the following sections, we review the key issues determining water intensity and provide some general rules that can be used to understand decisions about managing the water intensity of biofuel crops.

Plants and the water cycle

Plants obtain the water they need by uptake from the soil into their roots. The water in the soil comes from precipitation, groundwater and from irrigation. Water is lost from the soil by evaporation, drainage and uptake by plants, with different types of plant cover differing in the rate at which they withdraw water from the soil. As will be described in the following section, plants take up far more water than they ultimately use in photosynthesis or store as water in the plant structure. The remainder is released into the atmosphere in a process called transpiration.

Because the periods of maximum precipitation in the year may be out of phase with crop demand for water, storage of water in the soil plays an important role in supporting crops. The capacity of the soil to store water that is accessible to plants depends on the soil texture. Sands absorb water rapidly, but can store little and will

Figure 3.1



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Global annual precipitation in millimetres (mm)

drain quickly. A clay will not absorb water rapidly, making run-off and erosion more likely and, once it does absorb water, the clay particles bind water molecules, so some of the water in the soil is not available to the crop. Soil organic matter is critical in increasing the water-holding capacity of soils.

The water cycle in which plants participate provides essential ecosystem services, regardless of whether vegetation is native or non-native. Evaporation and transpiration also cool continental surfaces, which could otherwise be warmer in summer. At the same time these processes provide water to the air, which in turn falls as rain elsewhere. Indeed a major concern of Amazon deforestation is that it will cause increased regional droughts because less water will be evaporated locally to the atmosphere. Other types of ecosystem services include control of water flows into local streams and rivers, reduced nitrate leaching due to changes in peak flow drainage, and reduced soil erosion.

Figure 3.2

Schematic illustration of the water flows in biofuels production (not to scale). From left to right: precipitation over land yields groundwater, evaporation from the surface, or uptake by plants followed by transpiration; irrigation water can be drawn from aquifers, surface water or recycled water; surface water is fed by precipitation, run-off and groundwater, and loses water by evaporation and aquifer recharge; surface water is also removed for biofuel processing, with recycling to irrigation a possibility. The water cycle related to bioenergy conversion is discussed in the refining chapter.

Water intensities

Water intensities for bioenergy crops will be derived from information about volumes of irrigation water per hectare of crop land, mass (tonnes or kilograms) of biomass produced per hectare, volumes of biofuels produced per mass of biomass, and the thermal energy that can be delivered on combustion of the biofuel. The units will be m³/TJ for direct comparison with other water intensities in this handbook. Volumes of biofuels are also frequently expressed in litres: there are 1,000 litres in a cubic meter.

Irrigation and rainfall are often measured in terms of a depth of water, typically expressed in inches, centimetres or millimetres (mm). To translate the depths into a volume requires multiplying the depth of water by the area to which it is applied, i.e. 1mm of water applied to 1ha (10,000 m²) is 10m³.

Crop productivity (tonnes of wet or dried biomass per hectare and volumes of fuel extracted per tonne of biomass) are described in detail in a sister handbook, *Biomass for energy: an introduction* (released 2014 – see www.bp.com/energysustainabilitychallenge), and representative values used here are taken from values tabulated there.

The two biofuels that have demonstrated significant commercial use to date are ethanol and biodiesel. Their energy contents by mass and volume are^[5]:

Ethanol 29.6MJ/kg and 23.4 GJ/m³ Biodiesel 37.5MJ/kg and 33.0 GJ/m³



Plant water requirements

To understand the water demands of growing crops, it is necessary to understand the mechanisms that remove water from crop-covered land: evaporation and transpiration, collectively known as evapotranspiration (ET).

Photosynthesis and transpiration

Water is essential in the process of photosynthesis, in which plants use sunlight to drive the reaction of carbon dioxide from the atmosphere with water to form carbohydrates. The net photosynthetic reaction is:

 $\begin{array}{c} \text{Energy from sunlight} \\ 12\text{H}_2\text{O} + 6\text{CO}_2 & \longrightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 + 6\text{H}_2\text{O} \end{array}$

Pores in leaves (stomata) open to allow the diffusion of CO_2 into the leaves and, as they do so, water diffuses from the moist cell walls inside the leaf through the pores to the drier atmosphere. This process is known as transpiration and typically accounts for more than 99% of the water taken up by a plant. As shown in the equation above, part of the water that a plant takes up is chemically converted and retained in the plant as sugars, starches and structural materials. A small amount also remains in the plant to support non-woody structures: this is evident when plants wilt as a result of water shortage. The uptake of water from the roots also serves to carry nutrients in solution from the soil to the plant tissue.

There are three photosynthetic pathways, each of which has a different water requirement: C_3 , C_4 and CAM (crassulacean acid metabolism). The majority of plants (including barley, wheat, rapeseed, oil palm, all beans, rice and all trees) use C_3 , which is considered the most basic type. C_4 photosynthesis is thought to have evolved to increase the efficiency of photosynthesis relative to the amount of water transpired by plants in warm climates. It is used by some key crop plants, including maize, sugarcane and sorghum, as well as the emerging energycrops, switchgrass, energy cane, Miscanthus and Napier grass. The CAM pathway evolved as a water-conservation mechanism for plants in extremely water-limited environments. It is found in cacti and other desert succulents including agave, a potential biofuel source.

Table 3.1

Comparison of average yields (biomass in the above-ground parts of the plant) and annual evapotranspiration (crop water demand) for plant groups across the three major photosynthetic pathways: C_3 , C_4 and CAM^[6].

Agronomic traits	Photosynthetic pathway				
	C ₃	C ₄	CAM		
Average above- ground productivity (t ha ⁻¹ year ⁻¹)	35	49	43		
Water-use efficiency (kg ha ⁻¹ mm ⁻¹)	8-25	18-35	70–170		
Crop water demand (tonne H ₂ O ha ⁻¹ year ⁻¹)	14,000 - 42,000	14,000 –28,000	2,580 - 6,450		

The differences in water use for the different pathways are shown in Table 3.1. This shows that for similar levels of productivity, CAM plants have a water need far below plants with C_3 and C_4 pathways.

Water-use efficiency, relative humidity and vapour pressure deficit

For a given crop, grown under a given set of conditions, a water-use efficiency (WUE) can be defined as the ratio of yield of the crop to the evapotranspired water. Practically, it is measured in yield per area per unit of water, e.g. kg ha⁻¹ mm⁻¹. It can also be defined in terms of the photosynthetic reaction, as a ratio of the amount of CO_2 converted into biomass to the amount of water transpired. Different bioenergy crops with similar end-markets can have differing WUE and the same crop can have different WUE in different climatic zones. Matching crop species to local conditions can play an important role in optimizing the use of water resources^[7].

Relative humidity as a measure of the 'dryness' of the atmosphere is a significant determinant of rates of evaporation and transpiration, and thus WUE. The amount of water lost to the atmosphere depends on the difference in the humidity between the water-saturated soil or air inside the leaf and the usually less humid air of the atmosphere around the crop. This means that the same crop grown in a desert region will have a much higher water requirement than in a cooler temperate region, and thus a lower water-use efficiency. The effect of humidity on WUE can be quantified in terms of the vapour pressure deficit (VPD), which is the difference between 100% humidity at the local temperature (the saturated vapour pressure shown in Figure 3.3) and the actual humidity. Here is an example: if, at 19°C, the water vapour pressure inside a plant is 2.15kPa and the relative humidity of the air around the crop is 60%, then the vapour pressure deficit $is(1-0.6) \times 2.15 kPa = 0.86 kPa.$

Figure 3.3

Variation of saturated water vapour pressure (SVP) with temperature, showing the increase of SVP across a normal atmospheric temperature range. SVP is measured in kPa with 100kPa approximately equal to atmospheric pressure (1 bar).



The relative humidity is widely available from local meteorological stations or online^[8]. To better understand where low humidity will reduce water-use efficiency, the regional differences in VPD during the growing season, as shown in Table 3.2, must be considered. The values in the chart show that the VPD in semi-arid regions is typically about two to three times that in humid regions, and five or more times that in tropical regions^[9]. High VPD values generally, but not always, occur in regions of low precipitation.

Normalizing water-use efficiency to vapour pressure deficit

To a good approximation, for a given crop, the amount of evapotranspiration (ET, also often called crop water use) is directly proportional to the local VPD. As a result, if the absolute WUE values are multiplied by the local VPD, much of the geographical variation in WUE is removed. The result is a general normalized value for a crop, WUE_{VPD}, as shown in Table 3.3. Using the normalized value removes the variations due to local climate and reveals intrinsic differences, such as between C₃ and C₄ pathways.

Table 3.2

Vapour pressure deficit (VPD) for the growing season in different climatic zones, showing the typical range of the most common values of VPD. The full range of values whose extremes occur in very limited areas of each climate zone are listed in the right-hand column.

Climate type	Vapour pressure deficit				
	Typical range, kPa (most common values)	Full range, kPa			
Tropical wet	0.1-0.2	0.1-0.9			
Subarctic	0.2-0.3	0.1-0.5			
Tropical wet and dry	0.2-0.4	0.1-0.7			
Humid subtropical	0.4-0.5	0.2-1.1			
Humid continental	0.4-0.6	0.2-0.7			
Semi-arid	1.0-1.8	0.6-2.0			
Arid	3.0-5.0	2.0-7.0			

Estimating crop water use (ET) and crop yield using WUE_{VPD}

The normalized water-use efficiency, WUE_{VPD}, can be applied to different assessments. The first assessment is determining the crop water use (ET) needed to obtain a given yield. Given the desired or realized yield and knowledge of local precipitation patterns, the amount of irrigation needed can be determined. The basic equation for this calculation is:

ET = realized yield × VPD WUE_{VPD}

Given the value of WUE_{VPD} = 0.045 (t ha⁻¹) (kPa mm⁻¹) for wheat, a highly productive wheat crop producing 18t ha⁻¹ would have a crop water use of 400mm in eastern England, where the growing season average VPD is 1kPa, but 1,600mm in Egypt, where the VPD is 4kPa and the annual rainfall is much lower.

Similarly, given WUE_{VPD} = 0.095 (t ha⁻¹) (kPa mm⁻¹) for the bioenergy crop Miscanthus and a desired yield of 40t ha⁻¹ in Champaign, Illinois, the crop water use will be 631mm at a growing season daytime VPD of 1.5kPa,

which is just over half of the actual annual precipitation of 1,043mm. The same crop in western Nebraska, however, would have a crop water use of 1,263mm at a growing season VPD of 3kPa, almost three times the annual precipitation of 414mm.

An alternative use of the normalized WUE is to estimate the yield. The basic equation for this calculation is:

We can illustrate this for the yield of Miscanthus if it were grown in Nebraska and only received 200mm of precipitation during the growing season. Without irrigation or available soil water, the crop water use would be limited to 200mm. Given the values WUE_{VPD} = 0.095 (t ha⁻¹) (kPa mm⁻¹) and VPD = 3kPa, the yield in this case would only be 6.3t ha⁻¹, compared with the 40t ha⁻¹ yield available in Illinois where there is higher humidity and much more precipitation.

Table 3.3

Water-use efficiency normalized with vapour pressure deficit (WUE $_{VPD}$) for selected crops that use C_3 and C_4 photosynthetic pathways. The figures are normalized to take account of growing season daytime evapotranspiration. The average WUE $_{VPD}$ for C_3 crops is slightly over half that for C_4 crops.

C₃ Crop (country)	Scientific name	WUE (t kPa ha ⁻¹ mm ⁻¹)	C₄ Crop (country)	Scientific name	WUE (t kPa ha ⁻¹ mm ⁻¹)
Soybean (Australia) ^[10]	Glycine max	0.044	Miscanthus (England) ^[13]	Miscanthus x giganteus	0.095
Canola (Australia) ^[11]	Brassica napus	0.057	Sugarcane (Australia) ^[14]	Saccharum officinarum	0.083
Wheat (Argentina) ^[12]	Triticum aestivum	0.045	Cord-grass (England) ^[13]	Spartina cynosuroides	0.082
Willow (Sweden) ^[12]	Salix viminalis	0.048	Bulrush millet (India) ^[15]	Pennisetum typhoides	0.095
			Maize (US average) ^[16]	Zea mays	0.101
C ₃ average		0.049	C4 average		0.091

Agricultural water management and irrigation

Determining whether a crop needs irrigation and, if so, when the irrigation should be applied and in what amounts, is a key part of agronomy^[17]. Most crops have growth stages when water availability is particularly important: these are primarily germination, flowering and seed or grain formation. Drought after sowing can lead to crop loss, while water shortage at pollination or early seed formation can lead to empty or part-empty ears of wheat or cobs of maize. Short-rotation coppice and grassy biomass crops such as switchgrass, energy cane and Miscanthus, as well as sugarcane, are less vulnerable to transient drought. Tree crops and perennial grasses typically have deep, fibrous roots, and have access to a larger reserve of soil water than annual grain crops.

For crops to flourish, adequate water must be available during the growing periods. When this is unavailable from precipitation or soil water, irrigation may be employed. Most crops can tolerate some lack of water during the growing season and survive to the next rainfall, although yields may suffer. The benefits of irrigation must be weighed against the costs and practicalities so, in many situations, crops that would benefit are not irrigated. Worldwide, about 80% of all crops are purely rainfed.

Table 3.4 shows results for food crops, calculated using averages that take into account regional variations of crop water use (evapotranspiration) and how much of this water is supplied by irrigation. The global totals for both irrigated and rainfed show the need for caution in applying 'average' figures for irrigation as a basis for predicting future water consumption. It is also important to note that the irrigation figures calculated here represent the amount of irrigation water that is consumed. In reality, more water would be withdrawn and applied to the crops, with the excess returned to the local water system by leakage, run-off or percolation through the soil. The efficiency of irrigation practice, i.e. the amount consumed compared with the amount withdrawn, has been estimated at 38 - 56% in modern operations^[18]. This means that water withdrawal intensities for irrigation under present practice would be 1.6 - 2.7 times larger than irrigation water consumption intensities.

Irrigation water that is taken up by plants and released to the atmosphere through evapotranspiration is consumed - it is not returned immediately to the area from which the water was withdrawn. As noted above, however, more water is generally withdrawn for irrigation than is actually used by the crops. There are many known irrigation practices that can improve efficiency in water transfer, but these are often not implemented due to cost or increased operational complexity. These may include the use of mulches, cover crops, straw or artificial membranes to reduce evaporation from the soil surface. Other measures, such as contour ploughing and maintaining soil organic matter content, can decrease run-off and retain soil moisture. Finally, buried drip tubes and optimal scheduling to maintain soil moisture, rather than flooding the soil, can reduce withdrawal to become closer to consumption.

Table 3.4

Comparison of average yield, global production, water use and irrigation water consumed for three major crops that are used for both food/ feed and for biofuels. Modified from Table 8 in The green, blue and grey water footprint of crops and derived crop products^[19]. The average crop water use values shown here are the sum of the 'blue water' and 'green water' [19], and the average irrigation in the last column is the 'blue water' from the same reference. This table does not show the split of irrigation for biofuel crops versus food feed crops.

Crop	Farming system	Average yield* tonne/ha	World production million tonne	Average crop water use (ET) m ³ /ha/yr	Average irrigation calculated m ³ /ha/yr
Maize	Rainfed	4.07	456	4,404	0
	Irrigated	6.01	174	5,343	1,767
	Global	4.47	630	4,595	362
Soybean	Rainfed	2.22	158	4,615	0
	Irrigated	2.48	14	6,240	2,296
	Global	2.24	172	4,720	157
Sugarcane	Rainfed	58.70	580	9,627	0
	Irrigated	71.17	710	15,942	7,402
	Global	64.96	1,290	12,732	3,703

Note: data are for the period 1996 – 2005.

* Yields are typically reported with percentage moisture content of 15.5% water for maize, 13 – 20% for soybean, and 75% for sugarcane.

Water intensity of biofuels crops

Ultimately, we are interested in how much fresh water is withdrawn from local surface and groundwater sources and consumed in the growth of biofuels crops. As described above, we need first to estimate crop evapotranspiration and how much of the evapotranspiration volume is provided by irrigation. We then need to relate this to the energy content of the fuel produced, to determine the water consumption intensity. At present, the majority of commercial biofuel crops are grown in a relatively few locations. Following Schornagel^[18], we consider the irrigation practices, which provide withdrawal information, in those areas, and compare them with the most intensively irrigated examples outside the principal biofuel growing regions. The variations of irrigation practice are shown in Table 3.5. Estimates of withdrawal intensities are shown in Table 3.6. In most commercial biofuel irrigation schemes for sugarcane, maize and soybean, the range is between $4,000 - 7,000m^3/TJ_t$, which is significantly lower than the estimated average global withdrawals of water to produce food calories ($50,000 - 100,000m^3/TJ_c$ – see overview section). Water intensities can be further reduced for plants such as sugarcane, where water retrieved from the plant biomass is recycled along with plant matter for fertilization and irrigation. Similar practices are feasible with leafy lignocellulosic crops like Miscanthus. The growth of crops in areas that need significantly more irrigation (see Figures 3.5 and 3.6, right-hand columns) can, however, lead to higher intensities that approach those in the range of food crops.

Table 3.5

Comparison of the percentage by area that is typically irrigated for three major commercially produced biofuel crops. This ranges from 6% of maize in the US to 2% of soybean in US, Brazil and Argentina. Also shown is the maximum observed percentage irrigated for the three crops, ranging from 54% of the area under sugarcane in India to 6% of soybean in the US.^[18]

Commercially produced biofuel crop	Typical % by area of biofuel crop that is irrigated	Maximum observed % by area of biofuel crop irrigated
Sugarcane	4% (Brazil)	54% (India)
Maize	6% (US Midwest)	31% (US Texas)
Soybean	2% (US, Brazil, Argentina)	6% (US)

Table 3.6

Freshwater withdrawal intensities for biofuel crops, based on production practices for commercially produced biofuels from sugarcane, maize and soybean. For lignocellulosic crops, there are no commercial demonstrations and such crops are intended for rainfed growth. To provide a comparative reference, we show the intensities if 1% of the water requirements for these crops were to be supplied by irrigation. This table highlights water withdrawal intensities; consumption intensities will depend on irrigation practices, but will typically be about one-and-a-half to three times smaller.

Crop/fuel	Crop/fuel Crop yield/year* Fuel yield A vv (r		Annual or seasonal water requirements	Water withdrawal intensity 1,000m³/TJ Calculated using average of ranges			
			(raiman or irrigation)	Irrigation I	evel		
				Min (rainfed)	Majority practice	Max	
Sugarcane / ethanol	~ 70 tonnes/ ha ^[20, 21]	82 litre/tonne ^[20]	1,000 – 2,000mm Annual ^[21]	0	4.4	60	
Maize / ethanol	~9 tonne/ha ^[23]	390 litre/tonne ^[20]	670 – 790mm Seasonal ^[20]	0	5.2	26.7	
Soybean / biodiesel	2.4 tonne/ha (seeds) ^[20]	200 litre/tonne (seeds) ^[20]	450 – 700mm Seasonal, typically rainfed ^[21]	0	6.9	21	
Switchgrass / ethanol	10 – 23 tonne/ha Dry ^[20]	177 – 241 litre/tonne [20]	~700mm Seasonal, typically rainfed ^[24]	0	n/a	1% value for reference 0.9	
Miscanthus / ethanol	25 – 45 tonne/ ha ^[20]	310 litre/tonne ^[20]	750 – 1,200mm Seasonal ^[22]	0	n/a	1% value for reference 0.38	
Poplar coppice / ethanol	5 – 11 tonne/ ha ^[22]	~300 litre/tonne ^[22]	700 – 1,050mm Annual ^[22]	0	n/a	1% value for reference 1.6	

Note: where a range of water requirements is listed, the midpoint of the range was used to calculate the consumption intensitites.

* Yields are typically reported with percentage moisture content of 75% water for sugarcane, 15.5% for maize, 13–20% for soybean and ~ 50% for willow (wood). Usually switchgrass and Miscanthus are reported in dry tonnes.

Risks, opportunities and innovations

The primary water-based risk for biofuels is the possibility that growing biofuels could increase the demand for fresh water in water-scarce regions. Regionally responsible practices, in which biofuels are grown in areas where little irrigation is needed, have been demonstrated to be a sound approach to reducing water consumption intensity.

The main opportunity to reduce water consumption is by choosing crops that can withstand drought and survive with little or no irrigation. Many lignocellulosic crops fall into this category, as do CAM crops.

Opportunities for reducing water withdrawal intensity involve improving the retention of water in soils (so less irrigation is needed), and using more efficient irrigation

Chapter summary

Evapotranspiration, in which water from the soil is either evaporated or taken up and transpired by plants, is an ecosystem service provided by both natural vegetation and crops. Most plants, including 80% of all crops, rely solely on precipitation to support their transpiration needs. For commercial biofuel crops, common practice to date has been to grow them mainly in areas where little irrigation is needed; as a result their water intensities are significantly lower than the world average for food crops. Using the majority practice irrigation levels in Table 3.6, and the 2010 reported biofuels production^[25], it is possible to

practices with less leakage, run-off or diffusion of water outside the crop root zone.

Innovations in both food and biofuel crop growth are likely to include developing drought-resistant strains. Even with limited strain development, it will be possible to incorporate biofuels into an agricultural system to improve overall water management in local ecosystems. Appropriate choice and placement of crops can be designed to support flood control, minimize fertilizer run-off and even improve biodiversity. Such analysis requires understanding that the transpiration of rainwater, sometimes called 'green water' and counted as a water 'cost', is in fact an essential component of the ecosystem.

estimate world freshwater withdrawal for biofuels as about 20km³, around half a per cent of world freshwater withdrawals in 2010. Taking irrigation efficiencies of 38 - 56%, this corresponds to consumption of about 8 - 11km³.

Matching biofuel crops to areas where they grow well with little or no irrigation will be important in balancing the world's need for low-carbon fuels with sustainable use of freshwater resources. This requires regionally responsible decision-making.

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- For both refining and conversion of fossil fuels, there have been significant industrial demonstrations of reduced freshwater withdrawals and consumption by reuse, recycling and replacement with lower-grade water.
- The consumptive water intensity for refining crude oil ranges from approximately 5 – 26m³/TJ (about ^{1/5} to one barrel of water per barrel of product). The present water consumption intensities for refining biomass into biofuels are reported in the range of one to two barrels per barrel for biodiesel and four to nine barrels per barrel for ethanol.
- The estimated volume of fresh water consumed annually in the entire refining and conversion sector including biofuels is about 5km³, of which 80% is for refining crude oil.
- Based on an estimate that 25% of refinery capacity relies on once-through freshwater cooling, the volume of fresh water withdrawn for global refining and conversion is about 20km³, which is about half a per cent of total human freshwater withdrawals.

4 Water in refining and conversion

Introduction

In their native form, carbon-based energy sources (fossil fuels and biomass) need treatment to become useful gaseous or liquid fuels. Some processing will take place at the extraction site (e.g. coal washing and gas processing as described in the extraction section). Depending on the fuel type, additional treatment, refining or conversion may also be required.

- Crude oil is a complex mixture of different hydrocarbons and impurities, and is refined to create transportation fuels meeting a variety of different specifications, as well as a number of non-fuel products.
- Coal and natural gas can be chemically converted to produce liquid fuels that compete with fuels from refined crude oil.
- Biomass can be biologically converted (using fermentation) to create alcohols as a blend component or substitute for gasoline. Plant oils can be chemically converted to create esters as a blend component for diesel.

This chapter outlines the processes used to transform oil, gas, coal and biomass into marketable fuel products, and details where water is involved. In addition to the processes outlined here, there are many alternative approaches, especially for using biomass, that are in the early stages of research and development.

Refining crude oil to products

Oil is rarely extracted in forms that can be used directly so, since the 19th century, entire industries have developed to purify crude oil and transform it into valuable products, from transport fuels to plastics and pharmaceuticals (see Figure 4.1). Refineries combine thermal and chemical processes, most of which use water, either directly in the process or indirectly for thermal management.

Crude oil

Crude oil is a generic term for mixtures of naturally occurring liquid hydrocarbons that range widely in their physical and chemical properties. The mass energy density of the products (the amount of energy per unit mass) produced by refining depends on the ratio of hydrogen (H) to carbon (C) in the products: the higher the H to C ratio, the higher the mass energy density. In addition to the H to C ratio, the structure of the molecule also influences the properties of the liquid fuels that are refined from oil, such as how they evaporate and burn in an engine.

Because crude oil from different parts of the world can vary dramatically in chemical composition, refineries may be designed to refine a specific type



of crude, or to be capable of tuning their operations to handle changes of feedstock. In addition, refinery configurations can vary according to the desired product mix and to reflect different methods used to capture waste heat to improve efficiency. As a result, refinery designs are highly variable.

The most basic characteristic of the variability that refiners have to manage is the average molecular weight, with crudes ranging from light (low molecular-weight) oils that pour as easily as water, to extra heavy oils (high molecular-weight) that are solids at room temperature. This variability is well characterized by the density of the crude oil. The industry uses a measurement scale called the API gravity scale, defined by the American Petroleum Institute, in which the higher the gravity the lower the density (see Figure 4.2 on the next page).

Light crude oil yields a high percentage of valuable gasoline (petrol) and diesel fuel, with relatively simple processing. Producing such high-value products from heavy crude oil requires advanced techniques with increased temperatures, which demand more process water and more cooling water.

Figure 4.1

Typical product mix by percentage and volume refined from a barrel (159 litres) of crude oil ^[1] showing 85% as some type of fuel and the rest non-fuel products such as waxes, lubricants, asphalt and coke. A 159 -litre barrel of crude produces about 170 litres of refined product. The volume increase occurs because most of the products have lower density than the starting material.

Figure 4.2

The American Petroleum Institute's (API) gravity scale used to classify crude oil is shown on the bottom axis, while the mass density in units kg/m^3 is shown on the top axis. Note that the higher the API gravity the lower the density^[2].



Crude oil refining process

Crude oil entering a refinery is subjected to five main types of processing, illustrated in a generic plant layout in Figure 4.3. The stages of refining are:

1 Desalting

Crude oil generally contains some salts and a small quantity of water (less than $1 \%^{[3]}$) that have not been separated out of the oil in the field. The desalter removes salt impurities using process water. The heavier the crude oil being processed, the higher the temperature required in the desalter and, typically, the larger the amount of water required for washing.

2 Distillation

After desalting, the distillation process heats the crude, separating it into different hydrocarbon fractions, roughly according to the number of carbon atoms per molecule (molecular weight). In some refineries, vacuum distillation is used to recover additional heavy molecules (i.e. higher carbon numbers) that do not boil at atmospheric pressure from the residue. Process steam is used in the distillation to help vaporize and separate (strip) the components of the mixture.

3 Hydrotreatment

These processes include hydro-desulphurization to remove sulphur, and similar processes to remove other impurities (such as nitrogen and oxygen) from the process streams through reaction with hydrogen. Hydrotreating also converts unsaturated hydrocarbons (those with carbon – carbon double-bonds) to saturated hydrocarbons (paraffins). Process steam is used in hydrotreatment for separation (stripping) and may also be used for steam-reforming and water-gas shift (see GTL and CTL sections on pages 62 – 63) to produce hydrogen.

4 Cracking and coking

The heavier products leaving the distillation process and the residue that remains are broken down into smaller molecules or carbonaceous solids (such as coke) by the action of heat and/or catalysts. Catalytic cracking breaks larger molecules into smaller molecules that can be used in transport fuels, such as gasoline. Hydrocracking introduces hydrogen in the cracking process, making molecules that are more suitable for diesel fuel. Process steam is used to aid separation (stripping), as a diluent (reducing partial pressure), in the production of hydrogen and in catalyst reactivation. Coking is a process used on the residue from distillation. Heating the residue produces light molecules that can be further treated for use in transport fuels and petroleum coke, a carbon-rich solid.

5 Reforming and rearrangement

To maximize the production of gasoline, hydrocarbons can be reacted to produce molecules with appropriate properties. Those too light to be used in gasoline can be combined using alkylation into larger molecules, such as isooctane, shown in Figure 4.4, which is a valuable gasoline component. Molecules already in the gasoline boiling-range can be reformed or isomerized to increase their octane number. Stripping with steam is not standard for reforming because the light-volatile hydrocarbons present can be used instead. Steam, however, may be used in catalyst regeneration.

At the end of these processes, product output streams are cooled, blended and treated to produce marketable products to agreed specifications. The outputs include gasoline, kerosene, diesel, heavy fuel oil, gaseous fuels and base oils for lubricants.

Wherever water or steam comes into contact with hydrocarbons, oily sour (containing sulphur or other chemical contaminants) wastewater is generated. With appropriate treatment, much wastewater can be reused within the refinery.

Figure 4.3

Schematic flow diagram of processes and water use in a refinery with a hydrocracker. Actual configurations vary among operating refineries. Two streams of input water are distinguished in this diagram, one for cooling and one for process water, process steam and steam for heating. Most of the steam produced is used as process steam. Water output from each process is shown as brown arrows leading to the water treatment unit; there may be separation of different types of output water within this category that require different levels of treatment.



Figure 4.4

Structural model of an isooctane molecule^[4]: this molecule is made through reforming to raise the value of gasoline by increasing its octane number. The formal name of isooctane is 2,2,4 trimethylpentane.



Water in the refining process

Much of the water in a refinery is used in ways that has no contact with the oil. These include steam for heating and water for cooling. Cooling system types are similar to those found in thermal power stations, i.e. wet-tower and once-through, as described in the Water in electrical power production chapter, which starts on page 73.

When water does come into contact with oil, in many of the processes outlined above, water quality and potential contamination need to be addressed.

Input water quality requirements

For cooling, the water required need not be high quality, although hardness and salinity may have to be controlled to minimize scaling. Refineries may be designed to allow seawater, brackish or treated municipal water to be used. Many refineries are situated at the coast or on lakesides for such water access. Water can be treated and reused in refineries in order to contribute to the cooling water supply.

The requirements for process water, including water used to generate process steam, vary depending on where in the refinery water is required. Nearly all refinery processes use steam to enhance the distillation and separation processes. Any water supplied as steam to be used in chemical processes, such as the cracking process, has to be demineralized to prevent corrosion and scaling, whereas water used in the desalter can be recycled from other units within the refinery^[5].

Output water quality

The wastewater from a refinery consists of cooling water, process water, sanitary sewage water and rainwater. Issues of cooling water are discussed in detail in the chapter on power generation. Water that is in contact with oil during any stage of refining, including process water and steam, requires treatment before discharge.

Desalting water will contain dissolved chlorides in addition to emulsified and dissolved hydrocarbons; water used in the distillation, hydrotreating and cracking processes may contain sulphur compounds and phenols. Water required for washing equipment and infrastructure can pick up oil, as can rainwater falling on the processing areas of the refinery.

Treatment of refinery wastewater starts with gravity separators that allow solids to sink, forming sludge that can be removed for disposal and free-phase oil that floats can be skimmed off for reprocessing. Methods such as coagulation, flocculation and flotation are employed to remove emulsified hydrocarbons. Biological treatment systems involving micro-organisms are used to treat soluble hydrocarbons and other contaminants, by introducing oxygen to break down complex molecules. Any treated liquids that are not recycled or reused in the refinery are discharged from the treatment plant, and must meet or exceed local regulation. Solid wastes generated at various points during wastewater treatment are dewatered and normally disposed of in landfill sites.

Table 4.1

Water withdrawal and consumption for different processes in a refinery operating to the European Commission's Best Available Techniques (BAT)^[3, 7]. Intensities are expressed in m³/tonne throughput for the limiting case of 100% fresh water used in once-through cooling. Throughput refers to the amount of crude feedstock treated; the feed percentage column shows how much of the feedstock barrel enters each stage of the process. To calculate the water intensities in m³/TJ, every tonne of throughput is assumed to realize 0.9 tonnes of mixed product with an average energy content of 46MJ/kg. A more detailed breakdown of water intensity per product can also be carried out given a specific plant configuration^[6].

Process	Feed %	Cooling (m³/tonne throughput)	Process (m³/tonne throughput)	Steam (m³/tonne throughput)	
Desalting	100	n/a	0.05	n/a	
Distillation	100	5.2	n/a	0.035	
Hydrotreating	75	1.75	0.04	0.14	
Hydrocracking	18	1.8	0.005	0.005	
Coking	20	1.5	0.02	0.01	
Reformation/rearrangement	28	0.75	n/a	0.02	
Withdrawal and consumption intensities		Cooling	Process	Steam	Total
Max. freshwater withdrawal	m ³ /tonne throughput	11	0.115	0.21	11.3
if no recycle/saltwater cooling	m³/TJ	265	2.8	5	272.8
Approx. loss of cooling water	m ³ /tonne throughput	0.21	n/a	n/a	0.2
Freshwater consumption	m ³ /tonne throughput	0.21	0.115	0.21	0.5
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	m³/TJ	5	2.8	5	12.8

Volumes of water

The design and upgrades of each refinery include the choice of cooling systems and the source, reuse and recycling of water. Generally, newer refineries have lower freshwater consumption per unit of production than older refineries. As a result, there has been a global reduction in freshwater intensity over the past few decades.

Table 4.1 shows typical water flows and consumption for the process stages that crude oil passes through in a refinery with a hydrocracker. This example is taken from the European Commission's Best Available Techniques ^[3,7]. The values are based on 100% freshwater use in a once-through cooling water configuration. Many refineries instead use closed-loop (wet-tower) cooling or saltwater cooling, in which case the water withdrawal intensity will be much lower than the maximum level shown in the table. In Europe, the average consumption intensity is reported to be about $15m^3/TJ^{[3,7]}$, and in the US from about $15 - 26m^3/TJ^{[8]}$. Overall freshwater consumption intensity is dependent on the complexity of a refinery (number and sizes of processing units), the type of cooling and the type of water inputs. New refineries can be designed for efficient water use and existing refineries can be modified to improve water efficiency. Water audits improve water efficiency by showing where potable water can be replaced with lowerquality water and where there are water or steam leaks. Such audits also help managers identify where rainwater and site bore water can provide a significant resource; they also reveal opportunities to improve washing practices.

Where the availability of fresh water is compromised due to long-term droughts, increased cost or competition with other users, refiners can reduce their demands. There are many examples of upgrading at existing refineries – including plants owned by Exxon Mobil, Shell, Chevron and BP – that have dramatically reduced their withdrawals from local freshwater sources^[9–11]. As a specific example, Figure 4.5 shows the impact of water-use minimization initiatives between 1996 and 2009 at the BP Kwinana refinery in Australia. The efforts reduced fresh water use by 48%, potable water by 92% and wastewater flow by 47% ^[11].

Figure 4.5

Average daily freshwater intake and water-use intensity reductions for the BP Kwinana refinery in Western Australia^[11]. The refinery uses seawater cooling but has a similar level of process complexity to the European Commission's Best AvailableTechniques example. Application of water reclamation and recycling systems have reduced the withdrawal of fresh water from regional sources from about 0.41m³/t crude (10m³/TJ) in 1997 to approximately 0.23m³/t (5.5m³/TJ) in 2008. Changes included replacing potable water with lower-quality alternatives (including onsite bore water), through the installation of a waste reclamation plant and by improving processes and procedures. Values shown do not include salt water used for cooling.



Conversion of gas to liquids (GTL)

Natural gas can be chemically converted into liquid fuels to capitalize on the higher value of liquid fuels. An economical GTL process could be a powerful alternative to gas flaring, in which quantities of gas associated with oil production are burnt where there is not an economical way to transport the natural gas to market. The World Bank, which has been running a Global Gas Flaring Reduction Partnership since 2002, reports that more than 150 billion m³ of gas are flared annually, equal to about 4% of the world's total gas production^[12].

Turning gas into liquids has been technically possible since the invention of the Fischer-Tropsch (FT) process in the 1920s, and plants that use this in the back end of the coal-to-liquid process (see next section) have been running for more than 60 years. Many companies have invested in pilot plants but there is only a handful of commercial scale GTL plants operating or under construction. The largest is the Shell Pearl plant, in Qatar, capable of producing 140,000 barrels per day of liquid, with the nearby Qatar-Sasol Petroleum Oryx plant having a capacity of 34,000 barrels per day^[13–14].

Gas-to-liquids process

The generic chemical process for gas conversion is shown in the box on this page. First, natural gas is reformed into a mixture of carbon monoxide (CO) and hydrogen (H₂) called synthesis gas (syngas). The ratio of H₂ to CO is controlled to about 2:1 by adjusting the reforming process. The syngas is then converted via the FT process over a catalyst, producing a mixture of hydrocarbons. From a water-use perspective, the key point is that, because natural gas carries a larger H to C ratio than the resulting hydrocarbon product, the net reaction sequence produces a surplus of water.

With careful management to separate and recycle the output water, process water can be managed as a closed cycle and thus provide the water needed for other parts of plant operations; it may even provide a useful water product too. In addition to process water, cooling water is required for the GTL process. Where the cooling water is reused, some make-up water is required due to evaporative losses, although it could also be supplied from the FT reaction.

General chemistry of the GTL process

Generic reactions, representing the stoichiometry of feedstock to product, are shown below. Some intermediate mechanistic steps are omitted for clarity.

Syngas formation

Steam reforming $CH_4 + H_2O \rightarrow CO + 3H_2$ Oxygen reforming $2CH_4 + O_2 \rightarrow 2CO + 4H_2$

The balance of these reactions is adjusted to control the ratio of H_2 to CO in the syngas. (The water-gas shift, shown in the coal-to-liquid section that follows, may also be employed.) Excess H_2 may also be separated and used in subsequent product upgrading processes.

Fuel synthesis

Net alkane synthesis: $(2n+1)H_2 + nCO \Rightarrow C_nH_{(2n+2)} + nH_2O + side products$

The FT reaction sequence results in a mixture of alkanes with different chain lengths, as well as less desirable alkenes and oxygen-containing products. As in oil refining, the mixture may be treated by hydrocracking or hydrotreatment to eliminate the alkenes and oxygen-containing products as well as modify the molecular composition for desired fuel properties.

Water quality

As with most cooling processes, the water required for cooling need not be of high quality. Hardness and salinity may have to be controlled to minimize scaling but seawater, brackish or treated municipal water can be used with appropriate plant design.

Water in the reforming part of the process needs to be of high quality and therefore requires treatment to remove solid and dissolved contaminants.

The effect of the process on water

Cooling water will be effectively unchanged, apart from increased temperature and the salinity being raised due to evaporation. Water produced in the synthesis step will contain hydrocarbons and needs to be treated for reuse, recycling or prior to discharge.

Volumes of water

Just as the details of the reactions are not published for commercial reasons, data available for actual water use in operations are limited. A 2011 engineering report^[15] for a plant with wet-tower (evaporative) water cooling and significant recycling indicates withdrawal of 1.8m³ of water per m³ of product, and net losses of 0.7m³ of water per m³ of product (18m³/TJ mixed product). The losses are primarily due to evaporation from the cooling towers.

Where there is a significant water constraint, as at the Shell Pearl plant, dry cooling techniques and advanced water treatment for recycling, including ultra-filtration and reverse osmosis, can be used. Shell reports that no freshwater is withdrawn from local supplies, in part due to the generation of water in the synthesis process^[13].

Conversion of coal to liquids (CTL)

Rebirth of a technology

In 1812, Westminster bridge in London was illuminated by gas lamps, supplied from the world's first commercial gas works. There, coal was 'roasted' to produce town gas, a mixture of hydrogen, methane, carbon monoxide and volatile gases that rapidly became a prime source of heat and light. This technology was swept away, in most places, by the introduction of natural gas, but today there is significant interest in modern versions of coal gasification to produce liquid fuels and chemicals.

The processing of coal to form hydrocarbon liquids as a substitute for oil products has been possible on a large scale since the 1920s, via either direct reaction with hydrogen or hydrocarbons, or via the indirect Fischer-Tropsch (FT) process. It is currently only employed on a large scale in South Africa and China. The World Coal Association^[16] reported that South African capacity in 2011 was 58 million barrels of liquid, while the American Fuel Coalition reported that an Inner-Mongolia operation, using direct reaction, produced approximately 3 million barrels of product. To put this into perspective, the present annual production of CTL globally is roughly equivalent to one day's output from the world's oil refineries^[17].

Given the vast and geographically scattered reserves of coal, liquefaction or gasification are options for the future as alternatives to oil and gas. As shown below, however, the consequences for water use and greenhouse gas (CO_2) emissions are less favourable than for GTL conversion.

Processes

The chemistry of CTL processing using the indirect process with syngas (CO and H_2) as an intermediate is outlined in the box on this page. The essential result of the process, from a water perspective, is that there is a net consumption of water of approximately one water molecule per carbon atom in the output products.

This roughly corresponds to a volume ratio of about 1.5m³ of water consumed per m³ of fuel produced for the reaction alone. Additional water is also required for the purification steps and for cooling.

Water quality

As with most cooling processes, the water required for cooling need not be of high quality. Hardness and salinity may have to be controlled to minimize scaling, but seawater, brackish or treated municipal water can be used with appropriate plant design.

Water in the gasification and/or water-gas shift part of the process needs to be of high quality and therefore requires treatment to remove solid and dissolved contaminants. In addition, some gasifiers use water to quench the high-temperature gasification reaction.

The effect of the process on water

Cooling water will be effectively unchanged, apart from the temperature being increased and the salinity being raised due to evaporation. Water produced in the synthesis step and/or used in the gasifier will contain hydrocarbons and other pollutants such as sulphur compounds and needs to be treated for reuse, recycling or prior to discharge.

Outline of the chemistry of the CTL process

In the most common indirect route, variants of the FT process (which lie at the heart of CTL plant design) are preceded by a gasification stage to produce syngas, for which water is a key reactant.

As coal is deficient in hydrogen, water serves as a hydrogen source in the production of syngas in the gasification step. A significant portion of the water required for gasification can be obtained from water recovered elsewhere in the process.

The generic reactions in the gasifier, representing the stoichiometry of source to product, are shown below. Some intermediate mechanistic steps are omitted for clarity.

Syngas formation in the gasifier:

Steam reforming	$C + H_2O$	→	$CO + H_2$
Oxygen reforming	$2C + O_2$	→	2CO

Fuel synthesis

If a *cobalt-based* FT catalyst is used, the required 2:1 H_2 to CO can be generated by incorporating a water-gas shift reaction.

Water-gas shift: $H_2O + CO \Rightarrow H_2 + CO_2$

Using a cobalt-based FT catalyst, as in GTL, the fuel synthesis reaction produces H_2O as the oxygen-containing co-product.

Net alkane synthesis: $(2n+1)H_2 + nCO \Rightarrow CnH(2n+2) + nH_2O + side products$

If an *iron-based* FT catalyst is used, the \sim 1:1 H₂ to CO produced in the gasifier is sufficient. In this case, the fuel synthesis reaction produces CO₂ as the oxygen-containing co-product.

Net alkane synthesis: $(2n+1)H_2 + 2nCO \Rightarrow CnH(2n+2) + nCO_2 + side products$

For either catalyst type, the FT reaction sequence results in a mixture of alkanes with different chain lengths, as well as less desirable alkenes and oxygen-containing products. As in GTL, the mixture may be treated by hydrocracking or hydrotreatment to eliminate the alkenes and oxygen containing products as well as improve the mixture for desired fuel properties.

Whichever catalyst is used, the overall process requires the generation of CO_2 either in the water-gas shift reaction for cobalt or over the FT catalyst with iron. As a result, the CO_2 emissions for CTL synthesis are intrinsically higher than for GTL. In addition, the stoichiometry of the overall process requires consumption of one mole of water for every mole of carbon in the final product.

Volumes of water

Generic design requirements for water consumption in CTL processing are available in several reports and studies, as illustrated in Figure 4.6. A typical result for a plant based on the FT process, with a cooling tower and no recycling, indicates that up to 10m³ of water is consumed for every 1m³ of product. A large part of this is for cooling tower make-up that does not require highest-quality water. The variations in the reported values shown in the figure are due to differences in the chemical process, the variety of cooling technologies used and the fact that some plants use alternative sources of cooling water. The low value in the Rand study assumes air-cooling and maximum effluent recovery.

Figure 4.6

Water consumption intensities, in m³/TJ, reported in engineering studies and studies of operating CTL plants. An energy density of 44.2MJ/kg is assumed for the product stream (corresponding to a mixed product of petrol (gasoline) and diesel).



Biomass conversion to liquid fuels

Humans have been using biomass for energy since we discovered fire. Woody biomass is still used today for cooking and heating by a significant proportion of the world's population, and is also used in electricity generation.

Turning biomass into liquid fuels is relatively new, but most producers use adaptations of the centuries-old processes of fermentation and distillation to produce ethanol, which has a volumetric energy density about two-thirds that of gasoline. More than a century ago, Henry Ford built his iconic Model T to run on 100% ethanol, because he believed that the US could grow its own fuel. An alternative liquid fuel, biodiesel, is produced mainly from plants rich in natural oils, and the world's first diesel engine was designed by Rudolf Diesel to run on oil derived from peanuts.

The production of fuels from biomass is an area of dynamic research and development. Here we will focus on the two products that are in, or are near to, commercial production. These are bioethanol and biodiesel, produced from biomass grown on land.

Alcohols, mainly bioethanol, are used for blending with gasoline (petrol) and are usually produced by fermentation of plant sugars. In 'first generation' biofuels, the sugars are extracted from the starch or juice of crops such as sugar cane and maize (corn). In this case, crops are chosen to maximize starch or juice. In 'second generation' or lignocellulosic biofuels, the sugars are derived from breaking down the structural material of the plant. In this case, crops are chosen to maximize the yield of plant biomass. The output of the fermentation process is a solution of the alcohol in water, from which the alcohol must be removed, generally by distillation and drying.

Biodiesel, which can be used for blending with diesel, is produced by a chemical modification (transesterification) of vegetable fats and oils derived from plants or their seeds^[23]. The chemical conversion process involves a catalysed (the catalyst may be a strong base such as sodium hydroxide or an acid) reaction of the triglycerides in the oil or fat with a simple alcohol to produce esters, which can have an energy density more than 90% that of traditional diesel. The reaction product contains impurities and co-products including glycerol, soap and the original alcohol reactant, which must be removed.

Bio-refineries also often burn waste biomass to generate electricity and heat for both internal use and export, and some processes also generate co-products such as glycerol or animal feed^[24].

Fuel production processes and water use

Both bioethanol and biodiesel production require initial processing steps to isolate the parts of the plant to be used in the conversion to liquid fuels. Depending on the nature of the harvest, some plants need to be simply washed to remove residual soil. Extracting the desired components of the plant then can involve crushing or pressing, dry milling, or treatment with acid, enzymes or hot water. Much of the wastewater can be recycled for crop irrigation or fertilization.

Both ethanol and biodiesel production processes require water for cooling.

Bioethanol production

The fermentation process requires basic sugars as input. As illustrated in Figure 4.7, these are directly extracted from sugar cane as juice. Starch from corn and lignocellulose (woody biomass), however, must be chemically modified to release the sugars. For sugar cane, the cane is crushed to release the sugar, and the remaining lignocelluosic materials are left in a water-rich mixture of lignocellulose called bagasse, which can be dried for power generation. For corn, a slurry of the starch and water is cooked with enzymes to hydrolyze the starch into sugars. For lignocellulose, part of the plant material is a polymer called lignin, which is separated from the other structural materials, cellulose and hemicellulose. The lignin can be dried and burned to generate heat and electricity, or used to produce chemicals. The cellulose and hemicellulose are hydrolyzed with enzymes or acid to release the component sugars.

Figure 4.7

Schematic flow diagram of processes and water use in biomass conversion plants producing bioethanol. The initial steps for recovering sugars from sugar cane, corn and lignocellulosic crops are different, but lead to a common suite of steps for fermentation of the sugars and subsequent distillation to remove ethanol from the water-ethanol mixture, followed by drying to remove residual water. The yellow box depicts those steps where cooling and/or process water is required (not to scale).



Conversion process schematic adapted from work of Bruce Dale, Department of Chemical Engineering, Michigan State University.

Fermentation of the sugars takes place in a water-based environment with yeasts that have been optimized to metabolize sugars into ethanol. Fermentation requires a controlled temperature, and water-cooling is generally used as part of the thermal control. The fermentation output is a water-alcohol solution that must be distilled to separate the ethanol. Steam is used to provide energy in the thermal distillation process, and the water recovered from the product can be reused within the conversion plant. The sugar-based process yields a by-product called vinasse, which can be used in dilute form for crop irrigation, or concentrated for animal feed. The corn-based process yields a protein-rich product that is recovered for animal feed. Following distillation, the ethanol still contains a small amount of water, and it must be dried to yield fuel quality ethanol.

Biodiesel production

Some of the crops used to produce biodiesel, such as soybean, rapeseed and maize, yield seeds from which oil can be extracted mechanically by pressing. In large-scale plants, solvent extraction, which requires water cooling, may be used. The extraction of palm oil from palm kernels uses an initial step of cooking with hot water or pressurized steam.

Once the plant oils are extracted, they are purified using water, and then mixed with the catalyst (usually a strong base) and a simple alcohol (such as methanol). Purification of the mixture of chemicals that results involves water to remove the excess alcohol. The alcohol/water mixture is then distilled to recover the alcohol for reuse.

Water quality

Water of controlled quality is used to supply boilers for steam generation. Cooling water quality can be lower than boiler-feed water. Other refinery water needs, such as for washing, can be satisfied with water of lower quality.

Fresh water has traditionally been used in the chemical and biochemical reaction processes for bioethanol. Recent studies have shown, however, that some types of process wastewater can be reused in the biomass depolymerization and fermentation steps^[25].

Effect of process on water use

The processes used to produce bioethanol and biodiesel have significant differences, resulting in different contaminants in their wastewater streams. Fermentation of biomass to produce bioethanol results in wastewaters that are often rich in organic material with significant biological oxygen demand, as well as suspended solids consisting of unhydrolyzed plant materials and precipitated inorganic matter. These require treatment before recycling to fertilize crops, for reuse or for discharge. The processes involved in biodiesel production also produce effluent streams that require treatment before reuse or discharge.

Volumes of water

Data on water use is more extensive for bioethanol production than it is for biodiesel. In both types of production, a range of freshwater withdrawal and consumption is possible depending on replacement (use of low-quality or non-freshwater inputs), reuse or recycling, and the choice of cooling processes.

A survey of reports for biofuels processing is shown in Table 4.2.

Table 4.2

Examples of reported water withdrawal and consumption in the processing of plant biomass to produce bioethanol and biodiesel. The calculation of energy content per litre used values: for ethanol 29.6MJ/kg and 0.79kg/litre; for biodiesel 37.5MJ/kg and 0.88Kg/litre ^[26].

	Processing water (crushing, milling and refining)					
	Withdrawal		Consumption			
	Litre water/ litre fuel	m³/TJ	Litre water/ litre fuel	m³/TJ		
Ethanol from corn (dry grind mill, US) ^[27 – 28]	3	128	3 3.5-6	128 150 – 257		
Ethanol from sugarcane* (Brazil, averages) ^[29]	15-22	641 – 954	Consumption was about 20 – 30% of withdrawal in early reports			
Biodiesel from soy (US) ^[30]	—	—	0.5	15		
Biodiesel from soy (Australia) engineering study ^[31]	—	—	1.1	33		
Biodiesel from oil seed rape (Europe) ^[32]	—	—	2.6	69		
Ethanol from lignocellulosic biomass ^[33]	—	-	5.4	230		
* Withdrawal values for sugarcane ethanol include cooli	ng for by-product ele	ctricity generation.				

Bioethanol production from sugar cane in Brazil is an example of how water use may be improved, through recycling, reuse and technology improvements. Between 1990 and 2005 significant changes were introduced in Brazilian sugar cane mills. The aim was to reduce the total water withdrawal and consumption, and these changes ultimately led to significant improvements in water efficiency. One new technology introduced was dry-cane washing, which reduced the water withdrawals for washing by almost 80%. Similar process improvements and energy integration in distillation and evaporation reduced the total water withdrawal by sugar cane ethanol plants by about a factor of five between 1990 and 2005^[29].

The corn ethanol story in the US also follows the same trend. Dry mills, which constitute about 80% of corn ethanol production in the US, have been reported in Minnesota to have shown a 21% reduction in water use between 1998 and 2005. While older corn ethanol facilities used close to 11 litres water/litre ethanol, by 1998 this had dropped to around 5.8 litres/litre. The freshwater consumption in existing dry mill plants has declined to 3.0 litres/litre of ethanol produced^[27], while some engineering and design firms estimate the water consumption may drop to less than 1.5 litres/litre^[34]. Such high water efficiencies can be obtained mainly through capturing the water vapour from the dryer, by using air-cooled condensers for ethanol water separation, by recycling boiler condensate, and through several other process optimizations.

Lignocellulosic ethanol technologies are relatively new and processes to reduce water consumption by replacement, reuse or recycling have yet to be developed. Water consumption for processing lignocellulosic crops is projected to be higher due to the additional need to hydrolyze the cellulose and hemicellulose to the component sugars, and the added complexity of fermenting mixed sugar types. The engineering estimate for lignocellulosic ethanol production shown in Table 4.2 suggests that water consumption for the process is 5.4 litres/litre ethanol (230m³/TJ)^[33]. Close to three quarters of the water consumption can be attributed to evaporative losses of cooling water.

Risks, opportunities and innovations

As with other aspects of the energy supply chain, the risks due to water use in refining and conversion are regional, and involve both the impacts of water withdrawal and consumption, and the need for effective treatment of wastewater. Unlike other aspects of the energy supply chain, the conversion and refining processes often generate products additional to the liquid fuel product. These can include generation of electrical power, products such as coke or animal feed, and nutrient-rich water for fertilizing crops. The simple water intensities tabulated in this chapter are based only on the energy content of the liquid fuel produced. Where additional products like electricity and animal feed are produced, a full life cycle analysis would attribute some of the water consumed to these products.

High estimates of withdrawal intensities for cooling water used in fossil fuel conversion and refining are typically a few hundred m^3/TJ_t , which neglects the significant fraction of refineries that use saltwater cooling. The opportunities (including the use of seawater or dry cooling) for reducing freshwater consumption and withdrawal intensities for cooling are described in the Power chapter on page 73. There are trade-offs between water intensities, capital costs and energy efficiency for all the options.

The use of process water and steam is dependent on the engineering details of the refinery or conversion plant. With replacement, reuse and recycling of water, the freshwater intensities for processing in refineries can be significantly less than $10m^3/TJ_t$. Gas-to-liquids (GTL) is an inherently more water-efficient process than coal-to-liquids (CTL), but the demonstrated opportunities to reduce water intensity in commercial GTL plants could also be applied to CTL.

The use of process water for conversion of biomass to biofuels has some intrinsic differences to the refining and conversion of fossil fuels. A primary difference is in the initial stages of handling the biomass and extracting the components to be converted, and fermentation of plant sugars is carried out in a water medium. The wastewater generated in biomass conversion has a high organic content that is qualitatively different than the wastewater streams for fossil fuels conversions. The conversion of plant oils has process water demands similar to fossil-fuel conversion. In both cases there are significant opportunities for innovation in reuse and recycling to drive down the water intensities in biomass conversion.

Chapter summary

The refining and conversion sector has demonstrated the feasibility of significant reductions in freshwater withdrawal and consumption intensities by replacing fresh water with lower-grade water, by reusing water within plants and by improving recycling rates. As old plants are replaced and new plants are added, water efficiency measures based on replacement, reuse and recycling can be engineered into the systems along with new water-conserving technologies. If such good water practices are followed, the world's increasing demand for liquid fuels need not create a proportional increase in freshwater withdrawals and consumption for their processing and conversion.

To parallel the estimate of world water consumption provided in the Extraction chapter on page 17, we can similarly provide an estimate of the additional water used to complete the transformation of energy materials into commercial fuels (shown in Table 4.3). Crude oil refining dominates in water consumption, with a high-end estimate of more than 4km³. All the other fuels combined add another 1km³ to the total. A low-end consumption intensity, taken from the BP Kwinana refinery, shows that the world total could be reduced to 2km³ with close attention to water management. Estimating water withdrawals for refining and conversion is more difficult, as worldwide information on the types of cooling used is limited. Given that about 60% of crude oil is imported into countries^[35] where it is refined, it is not surprising that around two-thirds of crude oil refinery capacity is located near a seashore^[36], where seawater cooling is likely to be used. In addition, around 9% of the global refining capacity is in oil-producing countries located in water-scarce regions^[1] where brackish water, seawater or closed-loop cooling systems are likely to be used. To get a rough, high-end estimate of withdrawals, we therefore consider a case where 25% of refineries use once-through freshwater cooling.

Withdrawals can be taken as equal to consumption for the seawater and closed-loop refineries. The withdrawal value from Table 4.1 of 273m³/TJ, applied to the estimated 25% of refining capacity using once-through freshwater cooling, gives a rough value for the world total water withdrawals for crude oil refining of about 15.6km³. Adding the other refining and conversion process leads to an overall global withdrawal value less than 20km³. In combination with the estimated withdrawal intensity for the extraction of energy materials, this gives a value of about 30km³ for the extraction and processing of fossil fuels and uranium, which is only about three-quarters of 1% of total human water withdrawals.

Table 4.3

Estimates of consumption intensities used to illustrate world water consumption for refining and conversion. The range of values for crude oil is taken from the low end observed at the BP Kwinana refinery to the high-end value reported for the US. The values for the other processes are at the high end of ranges reported. For volumes, 1km³ is equal to one billion m³. For biofuels, the water intensities were taken for corn ethanol in North America, sugar cane ethanol in South America, soy biodiesel in South America and biodiesel from oilseed rape in Europe.

	Amount of fuel processed 2010 ^[37]		Consumptive water intensity	Water consumption estimates
Fuel type	Million tonnes of oil equivalent	Million TJ	m³/TJ	km ³
Crude oil refining	3,964	166	5.5 - 26	0.91-4.32
Gas processing	2,728	114	0.7	0.08
Gas-to-liquids	7.1	0.30	18	0.01
Coal-to-liquids	16.2	0.68	300	0.20
Biofuels conversion				
Ethanol North America	30	1.26	130	0.16
Ethanol South America	20	0.84	286*	0.24
Biodiesel South America	5	0.21	30	0.01
Biodiesel Europe	10	0.42	69	0.03
High-end total				5.32

* Water intensity for sugarcane ethanol include cooling for by-product electricity generation.

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- Electrical power production is a distinct part of the energy-water connection because of the significant requirement for cooling to dissipate waste heat.
- The amount of cooling required depends on the efficiency of the process, which is highest for gasfired power generation with present technology. The amount of water withdrawn and consumed depends on the type of cooling as well as the efficiency, with once-through cooling having orders-of-magnitude-higher withdrawal rates than closed-cycle or dry cooling.
- Approximately 450km³ of fresh water is withdrawn annually for electrical power production; however, annual freshwater consumption for global electricity is a small fraction of withdrawal, at only about 16km³.
- Phasing out freshwater once-through cooling in favour of alternatives would enable future increases in the world's power generation to be met with less-than-current water withdrawals, even with the addition of carbon capture and storage to coal-fired power generation. Consumption would increase, but remain a small percentage of world freshwater consumption.
5 Water in electrical power production

Introduction

The world consumes about 200 billion TJ (nearly 40% of its total annual primary energy of about 533 million TJ) for the production of electrical power. Energy delivered from the electrical power (about 21,400 trillion watt-hours (TWh)), in 2010 however, corresponds to only 77 million TJ_e. The remaining energy is lost as heat because globally the overall energy conversion efficiency is less than 40%^[1].

The vast majority of water withdrawn or consumed in electrical power generation is for cooling to carry away the waste heat. In fact, the efficiency of power plants depends on their ability to cool the turbines that lie at the heart of most electrical generating systems. Generators have a choice of cooling systems, which involve different possibilities for replacement and reuse of water. By comparing the water intensities of different fuels and cooling systems it is possible to see where changes can be made to reduce water use and to predict the water needs of the generating sector as it meets the rising global demand for electricity. The columns of steam that punch the sky above many thermal power stations cause many people to assume that electricity generation consumes massive quantities of water. The facts are less obvious than the plumes themselves.

To emphasize the distinction between primary energy and electrical energy, we will report energy delivery from electrical power in TWh, occasionally adding a conversion (1 TWh = 3600 TJ_e) to the equivalent energy in TJ for comparison purposes.

We will present water intensities in two ways: cubic metres per million watt-hours (m³/MWh) and cubic metres per trillion joules (m³/TJ_e). So, $1m^3/MWh = 278m^3/TJ_e$.

Generating electricity

In 1831, Michael Faraday described a phenomenon that literally changed the world: when a conductor is moved through a magnetic field, electricity is generated. The ability to transform mechanical energy into electrical energy underpins all of modern society. This has resulted in a global power industry whose water withdrawals, although large, are only a seventh of that of agriculture.

With the exception of photovoltaics and wind, commercial electricity generation is based on rotating generators driven by heat engines, most of which require water for cooling. The obvious sources of mechanical energy, at the time of Faraday, were water and steam. Water (hydro) power still provides about 16%^[2] of the world's electrical generation. Steam turbines now lie at the heart of almost all modern thermal power stations.

The steam to drive turbines is generated, or 'raised', by producing heat from a primary energy source. By far the most common is coal, usually pulverised to a fine powder. Oil-fired power stations, no longer common around the world, use very similar technology to coal. Nuclear fission, geothermal heat, biomass and concentrated solar power are also used to generate steam (see Figure 5.1).

Gas is also a common fuel for electricity generation but most gas-burning plants do not primarily use the fuel to generate steam. Instead, they burn gas directly and use the expanding exhaust to turn a turbine. To increase efficiency further, modern 'combined cycle' gas plants couple this gas turbine to another turbine that is driven by steam generated using the hot exhaust from the gas turbine.

Figure 5.1

Global breakdown of the generation of electrical power by energy source in 2010. Approximately three-quarters of the electricity was generated in thermal power stations that require cooling, much of which involves water. The electricity generated represents use of slightly less than 50% of global generating capacity ^[3].



The steam turbine

This elegantly simple device, invented by the Londonbased engineer Charles Parsons, paved the way for cheap and plentiful electricity. Steam turbines have at their core a rotor from which project several rows of closely spaced blades. Steam, generated outside the turbine in a boiler or steam generator to around 500°C and 170 bar (17,000kPa), enters the turbine casing and its expansion drives the turbine blades. At the exit from the turbine, the steam must be condensed so it can be returned to the boiler.

The steam cycle itself, shown in Figure 5.2, is a closed loop that circulates the expanded steam from the turbine to be cooled in the condenser. From there it is pumped back to the steam generator. Cooling is accomplished with a separate water stream that is isolated from the water in the steam cycle.

The water in the steam cycle occasionally needs to be replaced due to build-up of sludge, in a process known as blowdown, and water lost through steam leaks also has to be replaced. Fortunately, the volumes are small compared with cooling water use, at around $0.02m^3/MWh$ (5.6m³/TJ_e) for a typical US power plant^[4].

Cooling systems

Water used in cooling the condenser represents 85-95% of total power plant water use. The volumes used and the division between withdrawn and consumed depend on the type of system.

Once-through cooling

Once-through cooling is also known as open or open-loop cooling. As shown in Figure 5.2a, it is a process of withdrawing water from large surface sources, such as lakes, major rivers or the ocean, and returning it, after it has passed through the steam condenser and absorbed heat from the steam leaving the turbine. Using ocean water rather than freshwater sources is a replacement approach that reduces freshwater withdrawals for cooling to zero.

The large flows of water, and the increased temperature of the returned water can impact ecosystems negatively. Power plants relying on rivers have been shut down or had their production capacity reduced during hot spells and droughts when river levels are low^[5] or when regulators were concerned about the environmental consequences of adding extra heat to already-warm rivers.

Wet-tower (closed-cycle) cooling

Wet towers are the source of the iconic columns of steam so often associated with thermal power stations. As illustrated in Figure 5.2b, the cooling water is managed in an internal reuse cycle, where water that has taken heat from the condenser is pumped to the top of a large tower. There, the water is sprayed over a lattice of solid material, usually hardwood planks, that fill the tower. Air rises through the tower, either by convection or assisted by fans, cools the water and the latent heat of evaporation cools it more. Cooled water collects at the bottom of the tower and is recycled back to pass through the steam condenser again. Water is consumed by evaporation losses and some is purged from the system in the blowdown process (to avoid scaling) and is returned to the catchment area. The water used to replace these losses is called make-up water.

Wet-tower cooling withdraws far less water than once-through cooling, typically about ¹/₂₀ to ¹/₅₀ the amount, but part of the water withdrawn is consumed, leading to a corresponding increase in consumption intensity compared to once-through. Increased evaporation of the warmed water released from once-through plants is not included in this analysis. The wet-towers are sometimes the focus of community objections on aesthetic grounds, and the capital and running costs are higher than for once-through cooling.

Pond cooling

Towers can be replaced by large ponds if land is available. In these systems, water from the heat exchanger or condenser is run into ponds where evaporation and convection with the air bring about the necessary cooling. Withdrawal is low but consumption will be higher than for wet-tower cooling due to evaporation from the open ponds.

Dry cooling

These systems work in the same way as engines are cooled in cars, by passing large volumes of air over a heat exchanger, which is the steam condenser in Figure 5.2c. No water is withdrawn or consumed in these systems but they are more expensive to build and run than the other options. They also have an effect on the efficiency rate of the power plant of about 2%, depending on the ambient climatic conditions. Unfortunately for operations in hot areas, the biggest drop in output occurs when temperatures are highest, which is also when air-conditioning can cause demand to peak^[6].

Water quality

There is a significant difference between the quality of water required for cooling and that used in the steam cycle. Replacement of fresh water with lower-quality water is a viable option for cooling water, as plants can be designed to operate with water that is not fresh, including seawater. The input water primarily needs to have solids removed, pH adjusted and fouling minimized by the addition of chemicals. In contrast, the steam-cycle water has to be of very high quality and requires filtration, followed by the addition of chemicals to remove oxygen and control alkalinity.

Effects of the process on water

In once-through cooling, returning water to rivers or lakes even a few degrees above ambient temperature can affect the ecosystem. Water fed to boilers accumulates contaminants, which need to be periodically removed from the closed-loop system.

Figure 5.2

Schematic flow diagrams of cooling systems found in steam-driven electricity-generating plants. Diagram (a) shows once-through cooling, where water is withdrawn from a large water body and returned at a higher temperature. Diagram (b) shows wet-tower cooling, where cooling takes place by evaporation of water that is partially lost to the atmosphere in the process. Diagram (c) shows dry or air cooling, where air is drawn over a closed-circuit heat-exchange cooling loop. The heat source, steam generator and turbine/generator are not shown for dry cooling and wet-tower cooling but would have similar configurations (not to scale).







Water volumes and plant efficiency

For any type of cooling system, the amount of cooling water withdrawn or consumed is mainly determined by the power plant's thermal efficiency. Greater thermal efficiency means less waste heat to be rejected and thus less cooling water required per megawatt hour (MWh) generated.

The accuracy of available data on water use, on a global basis, is highly variable and includes outliers that likely represent faulty reporting or operational problems. To provide clarity on what is achievable under good operating conditions, researchers at MIT have devised a water-use model called System-level Generic Model (S-GEM)^[7] which provides a range of values for consumption and withdrawal of fresh water in thermal plants with different fuel types. Water use is influenced by:

- The efficiency of the plant.
- The cooling system.
- Other uses of water e.g. flue-gas desulphurization in coal-fired plants.
- Local climate.

The sensitivity of water consumption intensity to net plant efficiency given different cooling system types is shown in Figure 5.3.

Figure 5.3 illustrates the dependence of water consumption intensity – the volume of water withdrawn per unit of electricity (energy) generated – on efficiency. The data is from the S-GEM model, assuming a hypothetical case, where all S-GEM parameters are constant, only allowing efficiency to vary. The spread for each type of plant is illustrative of variations in efficiency due to different design, age and local climate.

In the following sections, each type of power generation shown in the figure will be described, and the consumption and withdrawal values will be reported along with values for operating plants from external sources.

The approximate global breakdown of types of water cooling for different types of power generation is shown in Figure 5.4. In the following sections, we quantify the impacts of different cooling types and power sources in terms of water use. In the final section of this chapter, we will consolidate the results, illustrating some ways to reduce freshwater use in power production.

Figure 5.3

For an electricity-generating plant, the sensitivity of water consumption intensity to net plant efficiency is illustrated for both wet-tower and once-through cooling, in a hypothetical case where all other S-GEM model parameters remain constant. The left axis shows intensity in m^3/MWh , with conversion to m^3/TJ_e on the right axis. This shows the consumption decreasing with increased efficiency and how once-through cooling consumes less water in power plants than wet-tower. This also shows the indicative increase in efficiency and reduction in water consumption from coal with carbon capture and storage (CCS), through nuclear to integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC). The figure is for illustrative purposes and tables later in this chapter should be used to find water consumption intensities of different generation technologies ^[4, 7]. Evaporation of warmed water released from once-through cooling plants is not included in this analysis.



V Figure 5.4

The distribution by percentage of cooling types in coal, gas and nuclear generating plants worldwide. The values are extrapolated from Platt's database of global cooling technologies, which does not cover all power generation^[6]. Extrapolation, taking into account total world generating capacity, is likely to overestimate the level of once-through cooling, since newer tower-cooled power generation capacity in Asia with lower withdrawals is not recorded as comprehensively as once-through cooled power plants in the US. The water-withdrawal intensities noted below each bar are explained in the following sections.



Coal - the single largest energy source for electrical power

Although a water wheel powered the world's first public electricity supply in 1881, Thomas Edison unveiled a steam-powered supply system in Holborn, London, only a year later. The fuel was coal, and coal has been the predominant fuel for generation ever since, today providing approximately 40% of the world's electricity needs^[2]. Water is involved in the production of every watt.

The coal-to-electricity process

Coal has the advantage of producing high temperatures with relative ease of handling. It can be supplemented by the addition of biomass material. A second method, gasifying coal to fuel gas and steam turbines in an integrated gasification combined cycle (IGCC) plant, has been demonstrated.

Pulverized coal (PC)

In PC plants, the workhorse of the industry, coal is ground to a fine powder before it is burned to heat the steam generator. Grinding the coal dramatically increases the surface area and causes it to burn in a similar way to a liquid fuel. A 500 megawatt (MW) plant burns around 250 tonnes of coal per hour when under full load.

In recent years, metallurgical developments have allowed plants to be built capable of running at temperatures and pressures above 374°C and 220 bar (22,000kPa). This causes the steam produced to be in a supercritical state: neither vapour nor liquid. These plants raise thermal efficiency from an upper limit of 37% typical in subcritical plants to around 43%, with subsequent benefits in fuel economy and reduction of carbon dioxide (CO₂) emissions. In 2010 the International Energy Agency (IEA) reported that some 20% of pulverized coal plants were supercritical^[8].

Integrated gasification combined cycle (IGCC)

In these plants, coal is combined with oxygen and steam to produce syngas, a mixture of carbon monoxide and hydrogen that fuels a gas turbine. The hot exhaust gases of the gas turbine are used to generate steam that drives a conventional steam turbine, and electricity is generated by both turbines. IGCC plants are more expensive than PC plants but can reach higher efficiencies. The extra efficiency and the use of a gas turbine that does not require water cooling results in lower water use than PC plants, although this is partially countered by the consumption of water used as steam in the gasification process. In 2010 the IEA reported that IGCC plants represented less than 3% of installed coal-fired generating capacity^[3].

Water use in coal-fired power plants

As discussed in the introduction, water use in thermal plants is dominated by cooling, with smaller amounts for make-up water for the steam cycle. Coal plants have a number of specific additional uses that, although requiring smaller volumes, also have a bearing on water requirements, in terms of both withdrawal and discharge.

PC ash handling

The fine ash resulting from burning pulverized coal, often referred to as fly ash, is cooled with water and can be transported as slurry, either for use or disposal. Uses include ballast and breeze-block manufacture but the majority is disposed of. The contaminants present in the coal, transferred to the ash, include a number of heavy metals and therefore disposal must be at sites isolated from the water table. Disposal sites require long-term surveillance and maintenance.

Flue gas desulphurization (FGD)

In the third quarter of the 20th century, the scale of damage recognized in Scandinavian and US forests as being caused by acid rain from coal-fired plants, both near and distant, brought about the wide-scale fitting of equipment to remove sulphur dioxide from the exhaust gases. The most common method of FGD involves passing the exhaust stream through a water-based scrubbing process, during which contaminants are passed to the water, most of which evaporates up the stack.

During the process, the water rapidly picks up sulphates and chlorides from the exhaust stream. Treating the output water to acceptable standards for discharge can require dedicated treatment plants.

IGCC syngas clean-up

The product of the gasifiers in IGCC plants contains contaminants that would foul the gas turbine. The current clean-up processes use water, and the output water requires extensive treatment before discharge.

Volumes of water

The consumption and withdrawal of fresh water for power generation based on coal is shown in Table 5.1, with a comparison of the engineering calculations (S-GEM) with literature values from operating plants. Non-cooling water typically represents about 10% of plant consumption and this is predominantly water used in FGD. Table 5.1 shows how strongly water intensities depend on cooling technology. The differences between once-through and other cooling types are far larger than the differences between generating technologies.

Table 5.1

Freshwater consumption and withdrawal intensities for different technologies of coal-fired electricity-generating plants using various cooling systems. The values are in m³/TJ_e. The data from the literature reports ^[8–17] are median values and the model results are from S-GEM ^[4, 7]. Evaporation of warmed water released from once-through cooling plants is not included in this analysis.

	Once-through freshwater cooling	Once-through saline water cooling (freshwater component shown)	Wet-tower cooling	Dry cooling		
Freshwater consumption values in m^3/TJ_{e}	9					
Coal – S-GEM	340	60	540	60		
Coal – values from literature	170	110	570	110		
IGCC – values from literature	—	—	319	—		
Typical freshwater withdrawal values in m^3/TJ_e						
Coal – S-GEM	36,000	60	640	60		
PC subcritical – S-GEM	—	—	705	—		
PC supercritical – S-GEM	—	—	629	—		
Coal – values from literature	31,000	110	700	110		
IGCC – values from literature	—	—	424	—		
Note: the volume of water in the saline column is fresh. We have not included the saline water used in this type of cooling.						

Gas - the power source that is changing the face of electricity generation

The economically recoverable reserves of gas are rising, and the advent of shale gas production has lowered the price of gas in North America and may subsequently be developed in other regions as well. This, combined with the lower CO_2 emissions of gas relative to coal and the flexibility of gas-fired plants, is making it the fuel of choice for many North American generators, and spurring interest worldwide.

The gas-to-electricity process

A 1930s invention, the gas turbine allows gas to be used more efficiently for electricity generation than is possible with a steam turbine. In the case of a gas turbine, expansion of the fuel gas during combustion directly drives the turbine blades. As a result neither the steam cycle nor its associated cooling water requirement is needed for a simple gas turbine.

The output heat of the combustion process can also be utilized: by capturing the hot exhaust gases and running them through a steam generator, a steam turbine can be powered in tandem with the gas turbine. This raises the efficiency from an average of less than 40% to in the region of 50 - 60%, placing these combined-cycle gas turbine (CCGT) plants well above the efficiency of other generation types. These plants can be fuelled by light oil or synthetic gas produced from coal gasification, but are most commonly fuelled by natural gas and are then referred to as NGCC plants.

Simple-cycle plants are retained almost entirely for short-term use to meet peak demand, whereas CCGT plants are used for base-load generation.

Water use in gas-fired power plants

The output of the steam turbine in an NGCC plant requires cooling to improve its efficiency, just as in plants using other fuels.

Water quality

As with steam turbines using other fuels, the quality of the water used in the closed-loop boiler cycle must be controlled to avoid corrosion problems. Cooling-water quality requirements are the same as for coal-fired plants.

Effect of process on water

The thermal effects and water-quality issues are the same as discussed above for coal plants.

Volumes of water

The consumption and withdrawal of freshwater for power generation based on natural gas is shown in Table 5.2, with a comparison of the engineering calculations (S-GEM) with literature values. Non-cooling water use is minimal, as there is no FGD or fly ash treatment required. No cooling is required in open-circuit simple-cycle gas turbines and, therefore, the water withdrawal and consumption is effectively zero.

Table 5.2

Freshwater consumption and withdrawal intensities for combined-cycle gas-turbine electricity generating plants using various cooling systems. The values are in m³/TJ_e. The data from the literature reports ^[8, 11 - 19] are median values and the model results are from S-GEM ^[4, 7]. Evaporation of warmed water released from once-through cooling plants is not included in this analysis.

	Once-through freshwater cooling	Once-through saline water cooling	Wet-tower cooling	Dry cooling		
Freshwater consumption values in m³/TJ _e						
CCGT – S-GEM	130	3	220	3		
CCGT — median values from literature	110	2	210	2		
Typical freshwater withdrawal values in m^3/TJ_e						
CCGT – S-GEM	16,000	3	260	3		
CCGT – median values from literature	12,000	2	270	2		

Note: the volume of water in the saline column is fresh. We have not included the saline water used in this type of cooling.

Carbon capture and storage (CCS)

- the aspiration of fossil fuel power without CO₂ emissions

CCS could play a significant role in addressing the global problem of rising atmospheric CO_2 levels brought about by man-made emissions. It is evident from oil and gas fields around the world that there are many geological settings capable of storing fluids for eons. In fact, CO_2 itself is a common gas found in hydrocarbon reservoirs and other geological settings. If CO_2 were captured at the points where it is produced and then injected into suitable rock formations, emissions would drop. All the elements of this engineering system are proven, but cost remains a problem and there is a significant implication for water use.

The CCS process

At present, CO_2 capture is only contemplated for large-scale fixed emitters, which include coal- and gas-fired power stations, along with refineries and industrial complexes such as cement works. CO_2 can be captured in pre-combustion, oxy-combustion or post-combustion processes:

- Pre-combustion refers to converting the fuel to CO₂ and hydrogen by gasification or steam reforming, separating the former and using the latter as a fuel for the plant.
- Oxy-combustion refers to burning the fuel in a stream of pure oxygen, which results in a concentration of CO₂ in the flue gas that can be effectively captured. Cooling the combustible gas stream is necessary in this technology and some of the CO₂ can be absorbed by cooling water.
- Post-combustion relies on separating CO₂ from the flue gas stream by absorbing it in a reagent, typically an amine, which on heating desorbs it.

These technologies work, as does the more mundane task of transporting CO_2 by pipeline. The oil industry has been doing that, harmlessly, for more than 50 years and has been injecting the gas into oil reservoirs for that length of time to enhance recovery.

Unfortunately, at its present state of development, CCS still has significant costs, both in capital and in the energy efficiency of the power plant when capture technology is fitted. Any reduction in efficiency results in greater cooling requirement to achieve the same output, and that will require more water where water cooling is used, as shown in Table 5.3. Also, energy is needed to transport and inject the CO_2 , which adds indirectly to the overall efficiency loss.

Water quality

With careful attention to engineering integrity that minimizes the possibility of amines being discharged accidently or mixed with any process water, capture technologies do not change the quality of water used in a power plant. Care is needed to isolate any potential storage reservoir from freshwater aquifers to prevent changing the pH of the aquifer.

Volumes of water

A decrease in power plant efficiency will bring about a roughly proportional increase in water intensity, as shown in Figure 5.5. The water intensity due to the addition of CCS ranges up to twice that without CCS, consistent with a previous report of an 80% increase^[17]. The figure shows a comparison of water intensities for coal and gas with and without CCS. Although the case of CCS with saltwater cooling is not shown, the replacement of fresh water with non-fresh water would give a much smaller impact on freshwater intensity due to CCS.

Table 5.3

Freshwater consumption and withdrawal intensities for CCS-equipped coal- and gas-fired electricitygenerating plants with wet-tower cooling. The values are in m³/TJ_e. The data from the literature reports are median values and the model results are from S-GEM ^[4, 7]. The table shows that, for the same cooling type, IGCC and CCGT/NGCC have approximately half the water intensity of pulverized coal ^[13, 15]. Evaporation of warmed water released from once-through cooling plants is not included in this analysis.

Freshwater consumption values in m³/TJ _e for wet-tower cooling						
	Pulverized coal with CCS	IGCC with CCS	CCGT/NGCC with CCS			
S-GEM	930	500	430			
Values from literature	940 570 400		400			
Freshwater withdrawal values in m³/TJ _e for wet-tower cooling						
	PC with CCS	IGCC with CCS	CCGT/NGCC with CCS			
S-GEM	1,100	570	520			
Values from literature	1,260	620	52			

Figure 5.5

A summary of freshwater consumption and withdrawal intensities for coal- and gas-fired electricity-generating plants using wet-tower cooling, with and without CCS. Values for plants using once-through cooling but without CCS are shown for comparison. The values are in m³/TJ_e. The data from the literature reports are median values and the model results are from S-GEM ^[4, 7]. These values are drawn from Tables 5.1 to 5.3. Note the discontinuity in the vertical axis. Evaporation of warmed water released from once-through cooling plants is not included in this analysis.



Nuclear - a low-carbon energy source

Nuclear fission is used to generate 13% of the world's electricity in some 433 reactors ^[20]. In August 2012 the World Nuclear Organisation reported that another 65 are under construction and 158 are planned. All of them rely on the steam cycle and hence use water both for steam generation and for cooling. No nuclear plants today rely on dry cooling.

The uranium-to-electricity process

Although the way energy is released in nuclear plants is fundamentally different from that of fossil fuels, these plants are just another example of thermal power production. Commercial nuclear reactors produce heat to boil water for the steam cycle with one extra fluid cycle, as shown in Figure 5.6. The heat from fission of uranium in the core of the reactor is transferred to the steam generator by a closed-loop fluid circuit, shown to the left of the figure. The most common reactor type uses water in these circuits, either pressurized or allowed to boil. The steam generated is transferred in another closed loop, shown in the centre of the figure, and this is used to drive a turbine. Engineering standards are rigorous to ensure that water that has passed through the reactor circuit does not contact water used in the steam circuit. Finally, a once-through or wet-tower cooling-water cycle is used to condense the steam for reuse in the steam cycle.

For safety reasons, nuclear plants produce steam at lower temperatures and pressures than coal- and gas-fuelled plants and, consequently, are less thermally efficient and require more water per unit of electricity for cooling.

Figure 5.6

Schematic flow diagram of water use in a generalized nuclear power station (not to scale). There are three separate fluid cycles: 1) a closed cycle for heat transfer from the core to the steam generator; 2) the standard steam cycle to drive the turbine; and 3) a standard once-through cooling cycle is shown; wet-tower cooling can also be used.



Water use in nuclear plants

In common with all plants based on the steam cycle, the vast majority of water use is for cooling. Not only are nuclear plants less efficient due to lower steam pressures and temperatures, but also they need to lose more heat through cooling systems, as none is being lost to the atmosphere via emission of flue gas, as is the case in coal and gas plants.

Cooling is critical around the reactor circuit, because reactors can fail if temperatures rise much above normal operating conditions. Another critical cooling process concerns spent fuel. In many reactors, fuel that has come to the end of its useful life is stored in ponds. As the fuel still produces heat, these ponds need to be cooled and this is normally done by circulating water. Nuclear plants must have large volumes of water available for cooling in emergencies.

Water quality

In the same way as steam turbines using other fuels, the quality of the water used in the closed-loop boiler cycle must be managed to avoid corrosion problems. Cooling water quality concerns are the same as for coal-fired plants. The cooling water for the steam cycle is isolated from the reactor and so it will experience no effect other than a rise in temperature, just as in coal plants. As with other power generation systems, water used in the steam cycle will contain concentrations of conditioning chemicals and need appropriate treatment before discharge. Some water used in the steam cycle will be mildly contaminated with radioactivity and can only be discharged back into the environment under strict controls. Still smaller volumes will be heavily contaminated and need to be disposed of in specially built facilities or stored until such facilities are available.

Volumes of water

As described above, nuclear reactors require more cooling water than coal plants. The intensity values shown in Table 5.4 are 20 - 40% higher than the corresponding values for coal-fired plants.

Table 5.4

Freshwater consumption and withdrawal intensities for nuclear-powered electricity-generating plants using various cooling systems. The values are in m^3/TJ_e . The data from the literature reports ^[8, 10-12, 15-17] are median values and the model results are from S-GEM ^[4, 7]. Evaporation of warmed water released from once-through cooling plants is not included in this analysis.

Once-through freshwater cooling	Once-through saline water cooling	Wet-tower cooling
380	3	660
0	0	700
49,000	3	790
46,600	2	1,160
	Once-through freshwater cooling 380 380 0 49,000 46,600	Once-through freshwater coolingOnce-through saline water cooling3803000049,000346,6002

Note: the volume of water in the saline column is fresh. We have not included the saline water used in this type of cooling. At present no nuclear power plants rely on dry cooling.

Concentrated solar power (CSP)

- a possible addition to the future power mix

Anyone who has burned a mark into a piece of wood with a magnifying glass will appreciate the potential of concentrated solar power. By arranging parabolic mirrors to concentrate solar energy on to a furnace, water inside the furnace can be turned into steam. This was demonstrated to Napoleon III in 1866, by the French inventor Augustin Mouchout, and the next century saw a number of solar steam systems. At the end of 2011 plants in Spain and the US had a combined capacity of nearly 2,000MW ^[18]. Most use steam turbines, but some rely on Stirling engines which do not use water.

Water use in CSP

The turbines in CSP schemes have water requirements comparable to those in nuclear plants. At present, the existing CSP plants use wet-tower cooling but, as the potential for large-scale utilization is primarily in arid areas, freshwater use will need to be reduced, with the most likely opportunities being replacement with brackish water, or the use of dry cooling.

In addition to water use in turbines, CSP plants use water for cleaning the mirrors, but the volumes are two orders of magnitude less than for cooling. Similarly, small volumes of water are also used to wash the cells in photovoltaic power generation. The water consumption intensities for CSP are shown in Table 5.5. The wet-tower cooling values are higher than for nuclear power generation, while the dry-cooling values are comparable to those for coal-fired power generation.

Table 5.5

Freshwater consumption and withdrawal intensities for solar-powered electricity-generating plants using wet-tower and dry cooling. The values are in m³/TJ_e. The data from the literature reports ^[19, 21-31] are median values and the model results are from S-GEM ^[4, 7].

Freshwater consumption values in m³/TJ _e					
Fuel type	Wet-tower cooling	Dry cooling			
Solar thermal – S-GEM	780	30			
Solar thermal — literature values	900	80			

Withdrawal intensities for wet-tower cooling are likely to be similar to the consumption values.

Geothermal - a power source of vast potential

Hot springs, volcanoes and working conditions in deep mines are all clear indicators of the heat that exists far beneath our feet. Although hot springs have been exploited for bathing and space heating at least since Roman times, it was only in the 20th century that the cause of geothermal energy was understood. The decay of radioactive minerals in the core and mantle of the earth provide about 80% of geothermal heat, with residual heat from the earth's formation making up the rest.

Commercial exploitation of geothermal energy has so far been limited to cases where shallow but hot geothermal reservoirs exist, which are usually associated with volcanically active areas of the earth.

The geothermal electricity-generating process

The pressurized hot water or steam available from a geothermal reservoir has a natural application in driving the steam cycle in a power generator. In 1904 in Larderello, central Italy, Prince Piero Conti tested the first geothermal power plant, and the world's first commercial plant was inaugurated there in 1911. Today, there is nearly 11,000MW of installed capacity in 24 countries^[2].

Hydrothermal geothermal (conventional geothermal)

Hot water or steam released when a well is drilled into a geothermal reservoir can be used in several different power-generation processes, depending on the temperature and pressure of the source fluid.

Dry steam

The first geothermal plants to be built used hightemperature steam with low water content, known as dry steam. Dry steam only emerges at surface in fields where the temperature of the rock that can be penetrated by wells is sufficiently high. The steam is often vented to the atmosphere after passage through the turbines. In this case no cooling water is needed, but the water in the reservoir may become depleted. Alternatively, condensing and reusing the water for injection is possible (see Figure 5.7).

Flash and binary cycle

Where hot water emerges at surface, this can be utilized in two ways depending on how hot it is:

• If the temperature is high enough, a system is used in which the hot water is channelled into tanks kept at a pressure lower than the production well. In the flash steam process, the pressure drop causes the water to flash into steam.

Figure 5.7

Schematic flow diagram of water use in a dry-steam geothermal power plant fitted with a condenser and a water reinjection system to maintain production in areas where the geothermal zone is not water-rich. After driving the turbine, the expanded steam is condensed, mixed with cooling water, and passed through the cooling tower for reuse as cooling water or for reinjection (not to scale).



• When the temperature of the emerging fluid is lower, an organic Rankine cycle can be used involving heat exchangers that contain a working fluid with a boiling temperature lower than water: this vaporises and drives turbines. These binary cycle systems are recent developments and can operate with water temperatures as low as 60°C.

As with dry-steam processes, water emerging from wells can be recycled to keep the underground system charged.

Enhanced geothermal

In addition to the geothermal reservoirs with appropriate characteristics to feed commercial power generation today, there are other methods proposed for capturing geothermal energy.

In projects known as hot dry rock or enhanced geothermal, holes are drilled into rocks believed to be at high temperature. Hydraulic fracturing is used to create multiple connecting fractures, so that water pumped from the surface down one hole can be recovered at the other, now much hotter and capable of driving a steam or organic Rankine cycle.

Water use in geothermal generation

Depending on the system configuration, water will be used for cooling and condensing the steam for reinjection, or to provide reinjection water. In enhanced geothermal, surface water is pumped into the subsurface heat source and is recycled back through the plant. Both cooling water and injection water can use low-quality water sources to replace fresh water. For instance, at the Geysers facility in California, treated municipal wastewater is injected into the hot rocks to maintain steam pressure.

Water quality

Unlike other steam cycles, geothermal plants use steam directly sourced from the subsurface, either as dry steam or as flash steam. Salts and gases in the water from the subsurface need to be managed in operations. The salts partly precipitate in the plant causing fouling, which has to be controlled, usually by periodic flushing.

Effect of process on water

The geothermal water is commonly either vented as steam or returned to the reservoir somewhat cooler and with a lower concentration of dissolved salts.

Volumes of water

Cooling water can be sourced either in the same way as for other generating plants or from excess geothermal fluid. Reinjection water can be sourced from geothermal fluid or from external sources, which need not be fresh water. A generic value for the cooling water consumption for closed-cycle cooling of a dry steam plant is $1,420m^{3/T}J_e^{[17]}$. Additional water consumption may occur if the reservoir water needs to be recharged. The US Electric Power Research Institute (EPRI)^[32] estimated possible losses of 5 - 15% for water cycling through an enhanced geothermal system reservoir, corresponding to a water consumption intensity of $622 - 1870m^{3/T}J_{ei}$ however, injection water need not be fresh.

Hydroelectricity - the clean, green power source, with some provisos

Water flowing due to the force of gravity has provided power since ancient times, and agriculture and industries have developed sophisticated machines to harness hydro energy. In 1887, an electrical generator was first turned by waterpower on the estate of English industrialist George Armstrong. It provided enough electricity to power one lamp. Today hydropower generates 16% of the world's electricity^[2], with countries such as Brazil and Norway deriving more than 85% of their power from hydro.

The process and its effects on water

Hydroelectric power plants all use turbines driven either directly by water flowing in rivers or from water collected behind dams. The range of size of plants is large, from microsystems delivering a few hundred watts, to schemes that transform entire catchment areas, such as the 22,500MW Three Gorges scheme in China. One trend that is creating a lot of interest, particularly in Europe, is low-head hydro schemes, in which new designs of groundworks and turbines can allow commercial quantities of electricity to be generated on rivers with only modest flow rates. Pumped storage hydro schemes can be built to store energy in mountainous districts. Water stored in a reservoir or lake at the top of a mountain can be released into a turbine lower down, which is used at different times as a pump to return water to the top of the system. This is particularly useful to meet short-terms peaks in grid demand and also to store energy produced by thermal stations, which have to continue operation even when demand is low. Pumped storage schemes are also useful in storing energy produced by intermittent alternatives, such as wind or solar.

As it is cheap and certainly has a low-carbon intensity, it is easy to think of hydropower as the ultimate clean, renewable energy source, but building dams and installing turbines in rivers affect water catchment areas. Dams change surface water evaporation patterns, and as a result it has been argued that some hydro schemes actually consume water^[33]. Far more obvious is the effect dams have on river flow, fish migration patterns and the downstream transport of sediment, vital to the renewal of agricultural land on floodplains. Despite these concerns, many developing countries view their river systems as potential electrical power sources. The deputy executive director of the IEA said in October 2012 that hydroelectric production could double worldwide by 2050, mainly through new schemes in developing economies.

Estimating global water impacts of power production

The largest process use of water in power generation is cooling, and the amount of power generated is expected to increase by more than 50% over the next 25 years^[3]. The following section outlines the impacts that the increased power production could have on freshwater withdrawal and consumption. The analysis considers the impact of potential future changes in the balance of different cooling technologies.

Global water quantities

Estimating the total amount of water withdrawn or consumed in electric power generation requires three pieces of information: the consumption and water intensities for each fuel and cooling type; the amount of electricity generated using each fuel type; and for each fuel type, the fraction of each cooling type that is used.

We know the water intensities, as shown in Figure 5.8 for oil and coal, gas and nuclear power generation. Since more than 95% of water withdrawals and direct water consumption for power generation can be attributed to coal, gas, nuclear and oil-fired thermal generation, considering these will give a useful estimate.

Figure 5.9

Estimates of global freshwater withdrawal and consumption volumes for coal-, oil-, gas- and nuclear-powered electricity-generation, based on S-GEM water intensities. The values are in km³ and are estimated using the 2009 data from Table 5.7, as described in the text. Water evaporated after release from a power plant is not included in this analysis or in the following tables and figures.



Figure 5.8

A summary comparison of S-GEM-calculated freshwater withdrawal and consumption intensities in m³/TJ_e for different cooling systems for coal-, oil-, gas- and nuclear-powered electricity generating plants.



We also need to know how much electrical power was generated using each of these fuels: the amount of the world's total electricity generated in 2009 for each was:

Coal	29.2 million TJ _e
Gas	15.5 million TJ _e
Nuclear	9.7 million TJ _e
Oil	3.7 million TJ _e

This leaves the final piece of information: the cooling types used for power generation with each fuel. The Platts database of global cooling technologies provides a large but incomplete compilation. For this estimate, we simply assume that the mix reported there can be extrapolated to the global mix, and that the distribution of cooling types for oil is the same as for coal. The extrapolation is likely to overestimate the amount of water required for oncethrough cooling, because Platts is known to report power plants more comprehensively in the US than in Asia. The resulting estimate of water withdrawal by cooling type and fuel source is shown in Table 5.6 along with the S-GEM water-withdrawal intensity values calculated for each case. The water intensities reported here are lower than, or at the low end of, ranges reported in many other recent publications ^[2, 34], which rely on survey methods. The engineering-based numbers presented here provide a useful base of comparison to the survey results, which are known to have difficulties with incomplete or inconsistent data, and which also tend to be biased toward North American and European data.

Based on the three sets of information above, the amounts of fresh water consumed and withdrawn worldwide for each fuel type and in total can be estimated. The results, shown in the Table 5.7, illustrate the vast dominance of once-through cooling in freshwater withdrawals. Freshwater once-through cooling systems withdraw more than 435,000 million m³ of water, which is 97% of the total withdrawal of fresh water for power production in 2009, and consume 3,900 million m³, 24% of the total fresh water consumed in power production.

3

49,000

3

380

Table 5.6

Percentage of cooling type and freshwater withdrawal and consumption intensities for coal-, gas- and nuclear-powered electricity generating plants. The distribution of cooling types is extrapolated from the Platts database^[6]. The values of water intensities are modelled using S-GEM ^[4, 7]. The 24% of the gas-powered generating capacity using gas turbines in open-cycle is excluded from the calculation.

Percentage generating capacity by cooling type (2009)							
Cooling type	Coal		Gas		Nuclear		
Dry	4.1%	4.1%		14.1%			
Wet-tower	50.1%		39.3%		33.0%		
Once-through saline	21.2%		29.1%		43.9%		
Once-through fresh	24.7%		17.4%		23.1%		
Freshwater intensity by cooling type (m³/TJ _e – S-GEM)							
Cooling type	Coal		Gas		Nuclear		
	Withdrawn Consumed		Withdrawn	Consumed	Withdrawn	Consumed	
Dry	60	60 60		3	n/a	n/a	
Wet-tower	640	540	260	220	790	660	

3

16,000

3

130

Table 5.7

Once-through saline

Once-through fresh

Estimated global freshwater withdrawal and consumption volumes for coal-, oil-, gas- and nuclear-powered electricity generating stations using various cooling systems, and S-GEM water intensities. The values are in millions of m³ and are estimated using the 2009 data from Table 5.6, as described in the text.

60

36,000

60

340

Volume in million m ³ (2009)								
Cooling type	Coal		Oil		Gas		Nuclear	
	Withdrawn	Consumed	Withdrawn Consumed		Withdrawn	Consumed	Withdrawn	Consumed
Dry	72	72	9	9	5	5	0	0
Wet-tower	9,371	7,906	1,185	1,000	1,202	1,017	2,531	2,115
Once-through saline	372	372	47	47	10	10	13	13
Once-through fresh	259,867	2,454	32,876	310	32,746	266	109,898	852
Total	269,681	10,804	34,117	1,367	33,963	1,298	112,442	2,980

Future water impacts

To predict how much water will be withdrawn and consumed for power generation in the future, we need to know how the amount generated and the mix of fuel and cooling types will change. The IEA New Policies Scenario projects changes in the amount and fuel mix as shown in Table 5.8, corresponding to an increase in power generation by about 65%. The change in the mix of cooling types will depend on decisions made about closing old plants and building new ones.

To illustrate the possibilities, two cases are considered. The first is a business-as-usual (BAU) cooling case, in which the mix of cooling systems stays the same. This would result in an increase from just over 450km³ of annual world water withdrawals to about 643km³ shown in the first two bar in Figure 5.10, and an increase in water consumption from 16km³ to 23km³.

The second case used for illustration is a new build case, where we estimate the water consumption and withdrawals that would occur if wet-tower cooling were used for all new plants. To carry out the estimate, numbers of new and replacement plants as projected in an IEA assessment, shown in Table 5.9, were used.

🔻 Table 5.8

IEA scenario of the change in electricity generated from 2009 to 2030 by fuel type (New Policies Scenario)^[3].

Electrical energy generated (millions of TJ_e)	2009	2030 (projected)
Coal	29.2	41.8
Oil	3.7	2
Gas	15.5	26.6
Nuclear	9.7	15.6

Using these values, we find that in the new build case (without CCS), water withdrawals could be reduced from 450km³ per year to 304km³ per year, a 32% reduction, while water consumption would increase from about 16.4km³ to 25.1km³. The withdrawal and consumption values are shown in the third and fifth bars in Figure 5.10.

The potential impacts of carbon capture and storage

One concern about implementing CCS in power production has been the potential impact on water demands. The estimated impact of adding CCS to coalfired plants is shown by the grey bars in Figure 5.10. The estimates are based on the S-GEM calculations (in Table 5.3) that indicate a wet-cooled coal plant with CCS will experience around 72% increase in both water withdrawal and consumption. If CCS were applied to all coal-fired power plants by 2030 in the business-as-usual cooling case, water withdrawals would increase to 921km3 per year, as shown in Figure 5.10. The impact on withdrawals, however, is greatly reduced if wet-tower cooling replaces freshwater once-through cooling, as in the new build case. If the replacements occur for new builds through 2030, the total water withdrawals would be no higher than the 2009 values, while consumption would increase to 42km3.

Table 5.9

Projections to 2030 for additions to and replacements of electricity generating plants. Values are in millions of $TJ_e^{[3]}$.

Generation	2009 – 2030 additions (millions of TJ _e)	2009 – 2030 replacements (millions of TJ _e)
Coal	23.1	10.5
Oil	1.1	2.8
Gas	16.1	5.1
Nuclear	8.5	2.6

Note: an interpolation was used to adjust the projection for a 2030 end-date.

Figure 5.10

Comparison of estimated freshwater withdrawal and consumption volumes for electricity generation in 2030 under the IEA New Policies Scenario, based on S-GEM water intensities. From left to right: reported withdrawals for 2009; projections for the business-as-usual case where today's mix of cooling types is maintained; withdrawals for the newbuild case where all new plants have once-through cooling. Consumption is for the newbuild case with an expanded scale to show detail. The CCS components represent the estimated impact of adding CCS to coal-fired plants.



Risks, opportunities and innovations

While globally the fraction of human water withdrawals used for power generation is moderate (about 10%) and the level of consumption less than 1%, power generation can unarguably have a significant impact on local water systems. Power generation presents risks of ecosystem damage, and conditions caused by high temperatures or droughts can lead to reduction of output and even shutdown.

Opportunities to reduce the freshwater intensity of power production primarily fall into the categories of replacement and regional responsibility, with efficiency also offering significant opportunities. Replacement is already a common technique in once-through cooling where plants can be designed to use salt water instead of fresh water. This is a particularly prevalent approach for managing cooling water for nuclear power. For wet-tower (closed-loop) cooling systems, however, reducing the water intensities shown in Figure 5.11 by replacement is more difficult, because the salts and other contaminants in lower-quality water can cause corrosion or foul the system.

There is the potential for technical innovation to allow lower-quality water use in wet-tower cooling. Wet-surface air cooling is designed to keep cooling surfaces continuously wet, slowing fouling and corrosion. Continuing development work is needed on materials that are both physically effective and cost effective, as well as on optimizing water treatment.

The ultimate replacement approach is using air instead of water for cooling. Because air cooling presents increased capital costs and decreased plant efficiency (especially when the external temperature is high), developing lowercost materials and improved plant design are opportunities to improve uptake of air cooling.

Regional responsibility issues in cooling can arise where there are seasonal extremes of hot weather that make dry cooling highly inefficient for just part of the year. Hybrid cooling systems represent a technical solution. One hybrid approach is using water spray in a dry-cooling tower during hot weather. If extreme heat conditions are longer, a parallel system of wet and dry cooling can be used, with the more water-intensive wet system brought online only as necessary.

Finally, efficiency offers direct benefits in reduced water intensity. More efficient fossil-fuel power stations, such as CCGT, reduce the demand for cooling water because there is less waste heat to be dissipated. In addition, where waste heat can be captured for space heating, or for use in industrial processes, its use will reduce demand for power and the associated water withdrawals and consumption.

Figure 5.11

Comparison of freshwater consumption intensities in m³/TJ using wet-tower cooling systems for the major electricity generating technologies. The values for this chart have come from Tables 5.1 to 5.5, which can be found earlier in the chapter. The increase in consumption when CCS is employed on coal- and gas-fired plants is shown. The value for geothermal steam is an estimate for cooling only.



Chapter summary

By far the greatest use of water in electrical power generation is in the cooling required to dissipate the waste heat from thermal stations. The choice of cooling system affects water withdrawal and consumption intensities more than fuel choice. Improved plant efficiency and the replacement of fresh water with alternatives (saline, brackish or wastewater, or air) for cooling offer significant continuing opportunities for reducing water intensities.

At present about 10% of the world's freshwater withdrawals are for thermoelectric cooling. If no changes in cooling technology were made in meeting increasing

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electricity demand, the volumes of fresh water withdrawn for power generation would increase by about one-third as electrical power generation increases by 65% in 2030 (IEA New Policies Scenario)^[3]. Changes in the types of cooling systems in newbuild power plants, however, will mitigate the scenario, and could decrease the 2030 withdrawal volume to about two-thirds of the 2009 withdrawal volume, even as the amount of power generated increases. In this scenario, even the addition of CCS to all coal-fired power plants would still result in 2030 withdrawal volumes lower than those of today.

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- Current delivery of suitable water and treating wastewater worldwide uses less than about 3% of the world's primary energy. The energy cost of treating all today's global wastewater would increase the world's energy required for water to about 5% of total energy.
- Where unpolluted ground and surface water is available for human consumption, the energy used for delivering water to and from users is dominated by water transport and treatment of wastewater (where it occurs), at electrical energy costs ranging from ~0.1–0.7kWh/m³.
- Desalination is more energy intensive, at ~0.5 – 4kWh/m³ for reverse osmosis with energy recovery, and is generally higher for thermal methods. Desalination currently meets about half a per cent of global freshwater demand.
- In terms of energy costs alone, long-distance transport of fresh water can compete with desalination when the transportation path doesn't include a large increase in elevation.

6 Energy in water systems

Introduction

The benefits of clean water and effective wastewater treatment, although well understood, are not available to all, as a consequence of both the amount of capital and energy needed to build and operate such systems. History is punctuated by the development of technologies to source, transport and dispose of water. They include Stone Age natural wells in Cyprus^[1] and Harappan man-made wells in the Indus valley^[2], water extraction and transport technologies such as the gravity-driven qanats of ancient Persia and the windmills of medieval Europe, London's vast sewage treatment scheme of Victorian England, and the nuclear-powered desalination plants of 21st century Japan.

This chapter describes the processes used to take raw ground and surface water, treat it where necessary to an acceptable standard, deliver it to agricultural, domestic and industrial consumers, and then treat and manage the wastewater as it leaves domestic and industrial settings. This chapter will discuss the energy needed to supply the large amounts of water humans withdraw every year and deal with the resulting wastewater (see Table 6.1).

Table 6.1

Estimates for annual regional freshwater withdrawals in km³ for different sectors from groundwater and surface sources in 2000 ^[3-9].

Freshwater withdrawals km ³	Agriculture			Industrial			Domestic		
Region	Groundwater	Surface water	Total	Groundwater	Surface water	Total	Groundwater	Surface water	Total
Africa	27	159	186	2	7	9	15	7	22
Asia	497	1,439	1,936	63	207	270	116	56	172
Latin America and the Caribbean	17	170	187	8	19	27	15	35	50
North America	99	104	203	18	234	252	26	44	70
Oceania	4	15	19	1	2	3	2	3	5
Europe	23	109	132	16	207	223	37	26	63
World	667	1,996	2,663	108	676	784	211	171	382

Sourcing water

Like all other land animals, humans have, throughout most of their evolution, only needed to rely on surface water (in streams, rivers and lakes). As growing crops and rearing animals became commonplace, human water needs increased and, if sufficient local supplies were unavailable, alternatives had to be found. Water was transported from nearby rivers or lakes by irrigation ditches. Observing springs and damp low-lying ground could have led to the first wells, with the earliest known from more than 10,000 years ago^[1]. Wells are still critical to a significant proportion of the human race, although in most places wells are now drilled by machine.

Today, sourcing fresh water to meet the increasing needs of the world's growing population is a major challenge. The task is complicated by the increasing salinity of water from some ground sources as local freshwater supplies are depleted, and also by anthropogenic pollution of a great number of surface water and groundwater sources.

Transporting water

Local water sources are often at a lower elevation than the desired point of water use. Lifting water from an aquifer (groundwater), river or lake (surface water) for human use requires energy. Animal power is still used in parts of the world, as are windmills. In developed countries, engines drive pumps. Steam engines were invented to lift water, and examples of 19th century pumping engines still draw visitors to watch them at work. Now, electric pumps pump water far more efficiently. Modern pumps can remove water from wells faster than the inflow can replenish it, so care is required not to over-pump the groundwater source.

Once lifted, water often needs to be transported to its point of use. Engineered systems to move water have been known since antiquity, with the Roman aqueducts and the qanats of the Middle East as prime examples. Such systems operated with no active energy input, because they were designed for water to flow under the influence of gravity. With the invention of pumps and affordable pipeline materials, the possibilities of moving water to any location became a reality.

Large volumes of water are now moved across hundreds of kilometres in infrastructure projects across the world.

Energy for moving water

The energy to move water depends on the volume, the height the water needs to be raised, the efficiency of the pumping and transport system, the distance and the desired output pressure.

With no output overpressure, the theoretical energy consumption to raise $1m^3$ of water through one metre is $0.0027kWh (0.0027kWh/m^3/m)$, presuming perfectly efficient pumps.

An energy consumption figure based on experience of running well-maintained systems with typical pump efficiency is 0.004kWh/m³/m.

The energy required to increase output pressure is approximately 0.042kWh per bar^[10].

The final factors influencing the energy cost for water transport are the losses of energy due to friction (the interaction of the water with rough pipe walls, bends Massive projects, such as Libya's Man-Made River that moves millions of cubic metres per day of groundwater from deep aquifers in the interior of the country to the coastal strip, have transformed the lives of many. Such projects have environmental impacts, however, and can give rise to inter-regional conflicts about water allocation.

and constrictions) and any losses due to leakages. Leakage losses are variable and difficult to quantify prior to construction and operation, but they can significantly affect system pressures and therefore increase energy requirements. Frictional losses are small in comparison with the energy used to lift water over even moderate slopes or generate excess water pressure. As a result, practically, the energy required to transport water can be reasonably calculated using the energy intensity estimate for lifting.

For systems that transport water over variable terrain, energy is often captured on downhill segments of the path using turbines to generate electricity, so it is reasonable to estimate the energy cost for lift based on the *net* increase in height.

Treating water

The coalition of UN agencies, UN-Water and the World Health Organization state that each person needs 20 – 50 litres of water per day, just for basic needs. One in nine^[11] of the global population still does not have access to clean water. The degree of treatment required to provide clean water, where water is available, obviously depends on the water quality at source. It also depends on the end use, ranging from raw untreated water for industrial cooling and washing purposes, through to water for agriculture, to potable water and purified supplies for use in power-station boilers.

This section outlines common practices for treating groundwater and surface water (schematically shown in Figure 6.1), the main methods of water purification and the ranges of energy required to power treatment systems. Because public information generally reports average values, and often does not separate the energy needed for different stages of treatment and pumping, the quantitative values shown should be taken as useful rules of thumb.

Groundwater supply

Groundwater usually has a low solids content, although it may contain dissolved gases, inorganic and organic chemicals, and micro-organisms. Gases are normally removed by aeration; oxidation and filtering remove iron and manganese; ion exchange is used to soften the water by removing calcium and magnesium; and disinfection, mostly with chlorine, is needed to remove microorganisms.

Supply from groundwater

The US Electrical Power Research Institute (EPRI) reports^[12] the energy intensity for groundwater supplied by public utilities in the US as 0.48kWh/m³.

Of this, about 30% represents energy for pumping water to the input of the facility and close to 70% is the energy cost for pumping water for distribution to the end-users. Less than 0.5% is used for chlorination.

In areas where aquifers are being depleted, the increased costs of pumping the input water from greater depths can be estimated using the energy values above for moving water.

Surface water supply

Water withdrawn from streams, rivers and lakes contains suspended mineral matter, biological impurities, plant material and man-made waste, both solid and dissolved. Surface water sources also often contain fertilizer residues from agricultural run-off or domestic and industrial pollutants, such as pharmaceuticals and organic solvents.

To cope with the range of contaminants, multistage treatment plants are employed to render water taken from open sources fit for consumption. Screens at the intake exclude larger solids. Mixing flocculating agents into the raw water and allowing settling time causes smaller suspended solids to drop out more effectively. Simple and effective sand filters can trap most smaller solids, and some treatment plants use activated-charcoal filters to remove organic chemicals before the water is disinfected with chlorine.

Supply from surface water

The EPRI $^{[12]}$ reports the energy intensity for surface water supplied by public utilities in the US as $0.37 kWh/m^3.$

Approximately 8% of this represents energy for pumping water to the input of the facility and 80–85% is for distribution to end-users. The remainder of the energy used is for the addition of chemicals, mixing, sedimentation and transport of water within the facility. Examples below illustrate the variability of reported electricity use for water treatment. Some may include input and output pumping, and different levels of treatment:

- 0.025kWh/m³ (US average)^[12-13].
- 0.41–0.8kWh/m³ (Canada includes input pumping; range includes differences in plant size – large (>5,000m³/day) to small (<5,000m³/day))^[14].
- 0.04–0.31kWh/m³ (New Zealand report states treatment processes only)^[15].

Figure 6.1

Schematic flow diagram for a generic water treatment plant with indications of where energy is used with the number of symbols indicating the proportion of energy used in individual processes. The upper part of the diagram shows how surface water is treated prior to distribution. The bottom left shows the treatment of groundwater, again prior to distribution. Input water quality, local legislation and the availability of investment will determine which elements of this system will be employed (not to scale).



Desalination - the quest for a limitless well

Introduction

If we could ever competitively — at a cheap rate get fresh water from salt water that would be in the long-range interest of humanity, and would really dwarf any other scientific accomplishment. John F Kennedy, 1962

More than 97% of the water on earth is too salty to be drunk safely by humans and animals. In addition to seawater, another 1% of the world's water^[16] (including much of the world's groundwater) is brackish, with a salinity between that of fresh and seawater.

Since the Second World War, desalination has been taken up in more than 150 countries^[17] and in 2011 there was an installed capacity of 77 million m³/day. While the volume of desalinated water is less than half a per cent of global fresh water demand, desalinated water is primarily used for domestic and industrial (non-cooling) applications, where it provides more than 3% of water consumed. Plants have been built to desalinate both seawater and brackish groundwater, and the technology has moved on significantly from simple distillation to systems that use sophisticated membranes for separation. All methods require energy inputs and energy costs are one, but not the only, significant barrier to growth.

Figure 6.2

Schematic diagrams for the four major desalination technologies, showing the role of energy.



How to desalinate

Desalination has four main steps:

1 Intake

Sourcing water and conveying it to the desalination plant. Energy use here is for pumping.

2 Pre-treatment

Removing suspended solids, controlling biological growth and reducing scale-forming and corrosive constituents prior to desalination. These processes vary, depending on the source of water and the desalination system used, but they all require energy to drive pumps and filtration equipment.

3 Desalination

Removing dissolved solids, primarily salts and other inorganic constituents. There are two main groups of technology – thermal systems and membrane systems.

4 Concentrate management

Disposing or reusing the waste residuals from the desalination system. The waste stream from all desalination plants consists of highly saline brines. The volume of the waste brine is determined by how much of the water from the input stream is recovered as fresh water. For single-pass reverse osmosis and thermal systems, recovery rates may be $10 - 50\%^{[18]}$, while higher recovery rates of 80 - 90% are reported for brackish water electrodialysis^[19]. The brine waste stream needs to be disposed of in ways that do not impact the environment. Usually, this is done by mixing the effluent with lower-salinity wastewater from other processes, by evaporation, or liquid crystallization as part of a zero liquid discharge system.



Desalination technologies

Thermal systems

These rely on boiling the water at less than atmospheric pressure. In a partial vacuum, the boiling point of water is lower than 100°C, allowing low-grade heat to be used. Consequently, many modern plants are sited adjacent to power plants to utilize heat that would otherwise be discarded. Thermal systems support 35% of the worldwide capacity for seawater desalination.^[20]

There are two main thermal methods in use: multistage flash distillation and multi-effect distillation.

- In **multistage flash distillation**, hot water is passed through a series of chambers, each one at a lower pressure than the previous. Water boils at a lower temperature in each successive chamber and the steam is condensed to produce fresh water.
- In **multi-effect distillation** plants, feedwater is heated by steam flowing through tubes in a primary vessel. Some of the water evaporates and this steam is used as the heat source in the next vessel, which is maintained at a lower temperature and pressure. This process is repeated in a series of vessels with the condensed steam being collected and cooled for export as fresh water. Multi-effect distillation has the advantage of running at lower temperatures than multistage flash distillation.

Membrane systems

Over the past 40 years, membrane systems have developed rapidly, as membrane technology and energy efficiency has improved. They are now at the heart of more than 60%^[20] of the world's total installed desalination capacity. Two main technologies are used: reverse osmosis (the most popular) and electrodialysis. Other emerging (but as yet economically unproven) technologies include forward osmosis, membrane distillation and electrochemical mediation.

- In **reverse osmosis** plants, salty water is pumped into vessels at high pressure. The vessels contain semipermeable membranes allowing water molecules to pass but not the salt ions, which are flushed out as a discharge stream. Reverse osmosis is considered more cost-effective than electrodialysis for the desalination of waters with total dissolved solids (TDS) of more than 3,000 parts per million (ppm).
- **Electrodialysis** relies on the ionic character of salts in seawater or brackish water. Instead of using pressure to force water through a membrane, an electric field is applied, which attracts the charged ions across the membrane leaving the desalinated water behind. Electrodialysis is considered to be more cost-effective than reverse osmosis for water with a TDS of less than 3,000ppm^[21].

Membrane systems require more pretreatment of the feedwater than thermal systems, because the membranes are more sensitive than heat vessels to fouling from sediments, oils and greases, which need to be removed. Energy inputs and capacities for the four main technologies are indicated in Figures 6.2 and 6.3.

Figure 6.3

Global desalination capacity totalling 23.8km³ in 2009, with percentages by type of feedwater and technology^[17].



Feedstock

Desalination was originally used primarily to treat seawater but the reverse osmosis technique is also used to treat brackish river and groundwaters. In some schemes, wastewater, including industrial wastewater, is treated by desalination. Produced water from coal, oil and gas operations in areas of water scarcity is a potential feedstock, especially where oilfield formation waters are only brackish.

Energy for different types of desalination

The amounts of energy required in thermal systems are largely fixed, regardless of the quality of water being treated. In membrane systems, however, the salinity of the feedwater dictates the energy required. The saltier the water, the more energy is required to drive water through the membrane. As a result, thermal systems have been more popular for seawater sites and membrane systems favoured for treating brackish water.

Typical total energy costs vary widely between the techniques, as shown in the table below. Membrane efficiency has improved dramatically over the past few years, with energy requirements halving (see Table 6.2).

Across the world, desalination plants are powered by a wide variety of energy sources. In the Middle East, oil and gas are used, while in Perth, Western Australia, wind turbines provide the needed electricity^[22]. Because cogeneration raises the efficiency of plants, it is natural that many are built in conjunction with power plants; chiefly in Japan and India, these include nuclear power plants.

Table 6.2

Energy requirements for thermal and reverse osmosis
(RO) membrane desalination showing electrical energy
values in kWh/m ³ and thermal energy values in
$MJ_t\!/m^3~^{[13,~23]}$. 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. Thermal energy for
desalination is usually supplied from low-temperature
steam extracted from an adjacent power plant. There is
a range of performance in different installed systems.

Technology		Electric kWh/m ³	al energy (MJ _e /m³)	Thermal energy MJ _t /m ³
Thermal	Multistage flash distillation	2.5 – 5	(9–18)	70–280
	Multi-effect distillation	1-3	(3.6–10.8)	32-72
Membrane	RO: seawater	2.2-8.5	(7.2-30.6)	n/a
	RO: brackish water	1.0 – 2.5	(3.6–9)	n/a

Desalination versus transportation

Compared to conventional treatment of fresh surface or groundwater, desalination is more energy intensive. However, if fresh water has to be pumped to high elevations or a long way to consumers, the energy cost of water transport can reach or exceed the cost of desalination. Figure 6.4 shows the relative energy usage for different net lift (elevation gain) and conveyance distances versus various desalination technologies. It also illustrates a number of conveyance projects in terms of their elevation gain and their energy costs. The chart illustrates the trade-off between transport and desalination only in terms of energy required. For example, in energy terms, transporting water in northern Spain from the Ebro River to Aguadulce, through a distance of approximately 700km, with an elevation increase of 1km, is reported to utilize more than 4kWh/m³. This exceeds the power requirements for reverse osmosis of brackish water, indicating that local desalination would be more energy effective if a source of brackish water is available. Energy use is only one factor in such decisions: environmental and political factors may lead to very different conclusions.

Figure 6.4

Comparison of energy requirements for water transport and desalination. The energy requirement to transport water across a range of distances and net elevation change is shown by the solid lines, each indicating a different overall slope (metres of elevation increase versus kilometres of distance transported). The fixed energy costs to supply water locally by normal treatment of fresh ground or surface water, or by reverse osmosis (RO) of brackish water or seawater, are shown as coloured horizontal lines and bars. Reported energy costs for different energy for desalination comes from Table 6.2 and the energy consumption of 0.004kWh/m^{3/}m was assumed for transporting water (see text box 'Energy for moving water' on page 94, including the comment on *net* elevation gain).



Wastewater treatment

The eradication of cholera from Victorian London, as a consequence of the pioneering sewage system of Joseph Bazalgette in the late 19th century, and the reduction of massive pollution in Lake Erie, North America, in the 1970s, are examples of why wastewater treatment is so important. Early treatment plants were powered by steam, often fuelled by methane produced from the effluent they were treating. Such fuel sources are being rediscovered, as concerns about methane emissions and energy requirements increase, along with increasing standards of purification.

Municipal treatment plants have to cope with waste from domestic and industrial sources. The former, although entering any given plant from a multitude of sources, tends to have a relatively consistent quality. Industrial waste varies dramatically and, in many countries, legislation is in place that creates a level playing field for the economic costs of treating waste to an acceptable standard before discharging it into the municipal system. As a result of such regulation, large industrial complexes, such as refineries and mines, have developed sophisticated treatment plants that treat water to a sufficiently high quality for it to be discharged directly into watercourses. In this section, the waste treatments and their associated energy requirements are described from the perspective of a municipal setting. Industrial waste may need different systems to cope with the pollutants in the waste stream and, although these vary widely, it is reported by the EPRI^[12] that, typically, industrial treatment requires one and a half times the energy of municipal waste.

Agricultural waste presents more complications, since it is not a point source and it is difficult to treat as an outflow. As a result, more rigorous water supply treatment is often needed to deal with agricultural pollutants.

Treatment processes

The aim of wastewater treatment is to create an effluent clean enough that can be recycled back into the water supply, pumped to industrial or irrigation use, or discharged back to the environment. Solid, chemical and biological contaminants have to be removed in a series of processes, all of which require energy input, mainly involved in driving pumps and stirrers (see Figure 6.5).

Figure 6.5

Schematic flow diagram for a generic wastewater treatment plant. The broadening arrow on the right-hand side indicates the cumulative need for energy with additional treatment steps. Local legislation for outflow quality and the availability of investment will determine which elements of this system will be employed (not to scale).



Primary treatment

As effluent enters a plant, screens, some with mechanical rakes, remove large solids and grit-sized dense particles are allowed to settle in specially constructed chambers. Pumping the grit to landfill is an energy-intensive process. After the removal of macro solids, the waste is channelled into clarifiers, which are large, shallow pools in which sludge settles to the bottom and grease and fat rise to the surface. The sludge is concentrated by mechanical stirrers and removed for additional treatment, while the floating material is skimmed off and, again, removed for additional treatment.

Secondary or biological treatment

After clarification, the biological content of the liquor emerging from primary treatment needs to be reduced or destroyed. This is carried out by microbes, which digest the organic material in a variety of processes aided by the introduction of oxygen. Systems range in energy intensity from low-energy trickling filter beds, through activated sludge where air is pumped into sludge held in large tanks, to biological contactors that use rotating discs, or membranes that hold bacteria and micro-organisms. Sludge produced in this stage of treatment has to be treated and disposed of in landfill or consumed by bacteria in anaerobic systems, a process that results in heat and methane, now often used to fuel electricity generation. Allowing the liquor to flow through constructed wetlands, where microbes abound, is proving an effective low-energy alternative to mechanical systems.

Tertiary treatment

Before discharge, the effluent, now with much reduced biological content, is treated with additional bacterial processes to remove nitrogen and phosphates. The effluent may be disinfected to remove any residual micro-organisms. The addition of chlorine was, until recently, the standard method but environmental concerns have led to increasing adoption of non-chemical methods. These either involve passing the fluids under strong ultraviolet (UV) lights or bubbling ozone through the liquid. Both of these methods require electrical energy.

Table 6.3

Energy requirements for the stages of wastewater treatment in kWh/m³ for plants in Australasia and the US. The range of intensities for secondary treatment reported in the US corresponds to a variation in plant size by a factor of 10.

Treatment stage	Australia/New Zealand ^{[13, 2}	24]	US [12]		
			Range for secondary treatment corresponds to variation in plant size from 378,500 to 3,785m³/day		
	Technology type	Energy intensity kWh/m ³	Technology type	Energy intensity kWh/m ³	
Pumping to treatment plant		0.04-0.19		0.003-0.014	
Primary		0.10-0.37		0.0024-0.044	
Secondary	Filtration (dual /micro/	0.40 - 0.82	Trickling filter	0.18-0.48	
	fiano membrane systems/				
	UV disinfection	0.021-0.066	Activated sludge	0.27 – 0.59	
	Advanced treatment	Unknown	Advanced treatment	0.31 – 0.69	
Tertiary	General	0.32-0.88	Advanced with nitrification	0.41-0.78	

Wastewater treatment energy requirements

The amount of energy used to treat wastewater varies widely, both within individual countries and between countries, as illustrated with examples in Table 6.3. A wastewater treatment facility will not use all of the treatments outlined above in a single plant and, although they may follow three stages of treatment, the choice of technology and system configuration will vary from region to region, even within a single country.

local water quality to ambient temperature. The size and efficiency of the plant, the technologies used, the system complexity and location will all impact the energy costs of any wastewater treatment process. The standard for discharge of treated water demanded by regulators will also influence the design process and, hence, energy consumption.

Plants will be designed based on a myriad of variables from

Estimating energy use for water

It is possible to obtain an understanding of approximate total energy needed, globally, for water supply and post-use treatment by using estimates of the volumes of water and the energy intensities as outlined in the sections above.

The combined energy intensities for supply and postuse treatment in different sectors are shown in Table 6.4 using EPRI 2002 data for the US. The lack of treatment cost for agricultural water represents common practice because agricultural waste is rarely treated, even though agricultural run-off water can carry significant pollutants.

Table 6.4

Energy intensities to supply and treat water for industrial, domestic and agricultural sectors in the US. Agricultural waste is typically not treated . The values are based on 2002 data from the US Electrical Power Research Institute ^[12].

Energy intensities kWh/m ³					
	Supply from	Supply from	Wastewater		
Inductrial	0 198	0.079	0.661		
	0.130	0.075	0.001		
Domestic	0.482	0.371	0.407		
Agriculture	0.185	0.079	n/a		

Much of the world's wastewater is discharged back into the catchment with limited or even no treatment, despite the human and financial cost of waterborne disease^[25]. To understand what would be needed to remedy this situation, the energy required to treat domestic and industrial waste worldwide can be estimated as shown in Table 6.5.

To estimate the energy required to treat water supplies, the energy intensities shown in Table 6.4 have been applied. To reflect the variability of wastewater treatment across the globe, post-use treatment intensities were applied to 80% of industrial and domestic wastewater in North America, the EU and Oceania, and to only 20% of wastewater in Africa, Asia and Latin America. Using these assumptions, we can estimate that 879 billion kWh is required for the supply and treatment of water for human use. If higher standards of water treatment were applied globally to deliver 100% post-use treatment for domestic and industrial wastewater, an increased value of 1,195 billion kWh of electrical energy would be required.

The quantity of electricity for water supply and treatment, estimated for 2000, corresponds to about 5.7% of the world's total electrical energy production that year. If all domestic and industrial water had been treated to average US standards in 2000, the fraction of energy needed would have increased by about 35% to 7.8% of the world's electricity production. The extra power required to support 100% treatment, approximately 315TWh, could be provided by around twenty 2GW electricity generating stations (see Figure 6.6 (a) and (b)).

Table 6.5

Electricity required, in billions of kWh, to supply and treat, post-use, the world's water: (a) estimate based on 100% post-use treatment globally; and (b) estimate based on treatment of 80% of industrial and domestic water in North America, the EU and Oceania, with only 20% treatment in Africa, Asia and Latin America. Estimates based on data from Table 6.1 and Table 6.4.

	Agriculture		Industrial		Domestic					
Required electricity (billions of kWh) for	Supply	Post-use treatment	Total	Supply	Post-use treatment	Total	Supply	Post-use treatment	Total	Total
a) Supply and 100% treatment globally	281	0	281	75	518	593	165	155	321	1,195
b) Supply and 80–20% treatment globally	281	0	281	75	293	368	165	65	230	879

Figure 6.6

Year 2000 energy for water data: diagram (a) shows regional energy requirements and diagram (b) shows energy requirements by sector, both in billions of kWh, to supply agricultural, domestic and industrial water, and treat post-use domestic and industrial water to average US standards. The blue columns are values for 100% treatment of industrial and domestic water, while the dark columns are for 80% treatment in North America, the EU and Oceania, with 20% treatment in Africa, Asia and Latin America. Agricultural wastewater is assumed to receive no treatment as per common practice. Calculated fromTables 6.1 and 6.4.





100% post-use treatment of domestic and industrial water in all regions.

📕 80% post-use treatment of domestic and industrial water in North America, the EU and Oceania; 20% post-use treatment in Africa, Asia and Latin America.

Risks, opportunities and innovations

Economic and increasing population growth places increasing demands on fresh water for human consumption, agriculture and industry. Managing water resources sustainably is essential for human health, for the environment and for economic development. Different choices about how to meet increasing demands for fresh water will create different changes in future energy use.

Opportunities to reduce freshwater withdrawals by replacement with desalinated seawater or brackish water, or reuse of wastewater, carry variable energy costs and can present environmental risks in disposal of the effluent. Technical innovation such as improved membrane technology or treatments for wastewater recycling may provide opportunities for increased replacement and reuse with lower energy requirements. The largest human withdrawals of water by far are for agriculture, but these are carried out with the lowest intensity of energy for water acquisition and treatment. Where there are increasing needs for irrigation water to improve agricultural efficiency in the future, there is a risk that energy intensity could increase due to water purification, longer transport distances or pumping from deeper aquifers. Regionally responsible practices to use irrigation water more efficiently provide the most significant opportunities for reducing the energy impact of water for agriculture.

Chapter summary

The worldwide volumes of water withdrawals from ground and surface sources, for agricultural, industrial and domestic use, are measured in billions of cubic metres. Nevertheless, the amounts of energy now used to deliver suitable water and treat wastewater are less than about 6% of the world's electrical energy, which equates to less than 3% of the world's primary energy use. This number excludes energy for end uses such as heating water for food, hygiene and industrial processes, which is included in some reports on energy for water ^[13, 26]. Desalination now provides more than 3% of the world's domestic and industrial fresh water. The electrical energy costs of desalination, ranging from 0.5 - 8.5kWh/m³, depend on the desalination method and the salinity of the supply water. While ~3% of the total world primary energy is significant, it is small enough that an increase of ~35% to improve water treatment standards worldwide along with another 10 - 20% for growth in withdrawals over the next decade^[27-29] would increase world energy use by less than 2% through to 2020. However, if the fraction of fresh water needing higher energy intensity treatment and transport costs increases, then energy costs for water could undermine potential improvements in world energy efficiency^[30]. Conversely, the use of improved technology in replacement and recycling of freshwater resources and regionally responsible water-use policies could limit the energy impacts of providing fresh water.

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Glossary

- **Alkanes** Also known as paraffins, alkanes are a relatively unreactive but combustible series of hydrocarbons (see Hydrocarbons), with the general formula $C_nH_{(2n+2)}$. Examples include methane, butane and octane. An alkane may be a gas, a liquid or a solid at 20°C.
- **Alkenes** Reactive hydrocarbons, with the general formula C_nH_{2n} . Examples include ethene and propene, also known as ethylene and propylene. Alkenes readily form chain molecules called polymers (such as polyethylene), which are the basis of the plastics industry.
- **Alcohols** Chemicals related to alkanes in which one of the hydrogen atoms has been replaced by a hydroxyl group (OH). Examples include methanol and ethanol. Alcohols are used in medicine, and in industry as solvents and fuels. Ethanol is the substance that makes drinks such as beer, wine and spirits intoxicating.
- **Amines** Organic compounds containing nitrogen in the form NR_3 where R can indicate hydrogen or an organic group. Industrially, amines have various uses, including the removal of carbon dioxide from flue gases.
- **Anaerobic fermentation** A biological process taking place in the absence of oxygen, in which sugars are broken down into alcohols and carbon dioxide.
- **Anthracite** Shiny black coal with a high carbon content and few impurities. Anthracite burns with a hot clean flame.
- **API gravity** A scale, expressed in degrees, defined by the American Petroleum Institute, that compares the density of petroleum liquids. Light oils have higher API gravity numbers than heavy oils.
- **Aquifer** A saturated layer of permeable rock from which water can be pumped to the surface.
- **Beneficiation** A term used in mining to describe the various processes used to separate minerals from their ores. It is also applied to the process of removing impurities from coal.
- **Biodiesel** A form of biofuel produced from vegetable or animal oil. Biodiesel can generally be blended with or substituted for diesel fuel.
- **Bioenergy** Renewable energy generated from biological materials.
- **Biomass** Plant material, such as wood and crop waste, that can be used to generate energy (bioenergy). Biomass can produce heat directly (as in a wood-burning stove), be used in a thermal power station to generate electricity or transformed chemically into liquid biofuels.
- **Bioethanol** Ethanol produced by fermenting crops products or residues. Bioethanol is typically used as a blend component or replacement for gasoline.
- **Bitumen** A mixture of hydrocarbons with high viscosity and density. It may be solid at ambient temperatures.

- Brackish water Water that is saltier than fresh water, but not as salty as seawater. Measured in terms of total dissolved solids (in form of salts)^[1], brackish water contains 1,000 – 10,000-mg/l TDS^[2] (see Water quality).
- **Carbon capture and storage (CCS)** The process by which CO_2 created by power production and industry is prevented from release into the atmosphere. CCS involves capturing the CO_2 (such as from flue gases) and typically injecting it into suitable rock formations for long-term storage.
- **Carbonaceous** Describes a carbon-rich substance, such as the fossil fuels coal and oil.
- **Coalbed methane** Natural gas found in association with most coal seams. Coal has a very high surface-area-to-volume ratio, so there may be large amounts of such methane adsorbed on to the coal surface.
- **Coking** An oil refinery operation that upgrades some feedstock into a coal-like material called petroleum coke.
- **Connate water** Water trapped in sedimentary rocks at the time of their deposition.
- Crop water use or demand, also known as evapotranspiration or ET (see next page) The amount of water evaporated and transpired from an area of crops, both the plants and soil surface, during its growing season.
- **Darcy** A unit used to quantify permeability (the ease with which a fluid flows through a porous material), often abbreviated as D, although d is the formal abbreviation. Units of one-thousandth of a darcy (millidarcy = md or mD) and one-millionth of a darcy (microdarcy = μ d or μ D) are used to express values for very low permeability rocks. If the darcy value of a rock is known, it is possible to calculate the rate of a fluid flow through that rock if the viscosity of the fluid and the pressure drop across the material are also known.
- **Desalting** Essentially a washing process to remove the salt impurities usually present in crude oil. Not to be confused with desalination, which is removing salt from water to purify it for drinking or other use.
- **Dewatering** The process of removing the water from coal deposits to initiate the flow of coalbed methane.
- **Enhanced oil recovery (EOR)** A range of techniques used to extend the economic life of an oilfield after the easily extracted oil has been removed. They often involve injecting water with chemical additives and/or hydrocarbon gases or CO_2 into a partially depleted oil reservoir.
- **Enrichment** In the context of nuclear energy, the process of treating naturally occurring uranium to increase the proportion of the useful U²³⁵ it contains relative to U²³⁸.

- **Evapotranspiration (ET)** The process of evaporation from an area of vegetated ground, which includes both the water evaporated from the ground surface and that evaporated from the plants, the latter also being known as transpiration (see Transpiration). Although two different sources of water transfer to the atmosphere, practically it is difficult to separate them except under experimental conditions or in terms of theoretical models.
- **Flash steam process and binary cycle** The flash steam process is a means of using geothermal energy applicable to water at high temperatures of at least 180°C. Hot water emerging at the ground surface is channelled into low-pressure tanks, where it 'flashes' into steam in response to the drop in pressure. The steam is used to drive a turbine and generator.
- **Flowback** During hydraulic fracturing, large volumes of water-based fluid are pumped into rock formations. A proportion of this water then returns to the surface as part of the produced water, and must be disposed of carefully because of the additives and contaminants picked up from the reservoir it contains.
- Flue gas desulphurization (FGD) Various processes used to 'scrub' sulphur dioxide (SO₂) from the smokestacks of fossil fuel power stations. Because SO₂ is an acidic gas, the basic principle involves reacting it with an alkali such as lime.
- **Fresh water** Commonly used term to distinguish river water from brackish or seawater. Definitions vary, but fresh water generally has total dissolved solids (TDS) of less than 1,000mg/litre^[3]. This definition does not take into account other contaminants such as organic chemicals (see Water quality below).
- **Ganats** Ancient but sophisticated water supply systems involving wells and tunnels. Also known as qanats.
- **Groundwater** Water held below the earth's surface in soil and rocks.
- **Heavy oil** Precise definitions vary, but heavy oil is oil that does not flow readily at room temperature. Its viscosity is similar to that of treacle or molasses (see Figure 4.2, page 58).
- **Hydraulic fracturing ('fraccing')** A process whereby oil and gas are obtained from reservoir rocks that have very low permeability. A fluid is pumped at high pressure down a wellbore to create cracks in the rock, and 'proppants' (see Proppant) in the fluid prop open the newly created fractures, allowing the oil or gas to be extracted.
- **Hydrocarbons** Molecules consisting entirely of carbon and hydrogen atoms. Petroleum and natural gas are examples of mixtures of hydrocarbons.
- **Hydrocracking** A process that turns low-quality, heavy oils (hydrocarbons) into more useful products such as petrol and diesel fuels. Catalytic 'cracking' breaks the large molecules into smaller ones, and reaction with hydrogen creates the new hydrocarbons.
- **Hydrotreatment** A process within oil refining in which impurities are removed by reaction with hydrogen.
- **Igneous** Rocks such as granite and basalt that have formed as a result of the cooling and solidification of molten material in or at the surface of the earth's crust.

- **Injection water** Injection water is pumped into an oil reservoir, either to maintain pressure in the reservoir and/or to sweep oil towards production wells in a process called waterflood. Injection water can be recycled for repeated use.
- **Isotope** One of two or more forms of the same element differing from each other in atomic weight and nuclear properties. In nuclear power production, the useful isotope of uranium is U²³⁵.
- **Kerogen** Organic material trapped in sedimentary rocks, that has not been subject to sufficient temperature for conversion to hydrocarbons. They typically have a higher O:C ratio and lower H:C ratio than hydrocarbons.
- **Kilowatt-hour (kWh)** A watt is a measure of power (energy used over time) that equals one joule per second. A kWh therefore equals 1,000 watts produced or consumed for one hour. One kWh is equivalent to 3.6 megajoules.
- **Leachate** Leaching is used in mining to recover mineral by a process of dissolving the ores while they are still in situ. The resulting liquid from which the solids are precipitated is known as leachate.
- **Lignite** Low-quality, geologically immature coal, sometimes called 'brown coal'.
- **Lignocellulose** A combination of three polymer types that provide the structural material of the plant. The first is cellulose, a long linear polymer of glucose residues, which are held together by hydrogen bonding to form microfibrils. These are embedded in a matrix of a second polymer, hemicellulose, which consists of residues of a range of 5- and 6-carbon sugars. The matrix may also include a third polymer, lignin, which consists of randomly cross-linked phenolics. The cross linking provides rigidity, as found in wood. Lignocellulose is typically all that is left in crop residues, such as wheat straw and corn stover, and accounts for the bulk of wood.
- **Make-up water** The water that is added periodically to top up the water circulating in a steam turbine circuit.
- Methane hydrates Ice-like deposits of methane where the methane is held within a crystalline structure of water. They are found largely in ocean floor sediments and onshore, in Arctic regions.
- **Oil sands** Also known as tar sands, these deposits are mixtures of bitumen, sand, water and clay.
- **Oil shales** Sedimentary rocks that contain organic-rich solids called kerogens.
- **Organic Rankine cycle** The organic Rankine cycle transforms thermal energy into mechanical energy, using organic fluids that have a lower boiling point than water. The fluid allows heat recovery from low-temperature sources.
- **Permeability** The degree to which a liquid or gas can flow through a porous material.
- **Porosity** The spaces between the grains that make up a rock are called pores and porosity refers to the proportion of pores within a rock, often expressed as a percentage. Pores may contain water, oil or gas.
- **Potable or drinking water** Water that is safe for human consumption without requiring any treatment beyond its current state.

- **Produced water** Water trapped underground, in oil and gas reservoirs, which is brought to the surface during extraction. It is often recycled and used in related processes.
- **Proppant** In hydraulic fracturing, the proppant consists of grains of solid material (such as sand) that prop open the fractures created by forcing water at high pressure into rocks containing gas or oil.

Renewable fresh water resource (RFWR)

- The amount of fresh water made available annually through the hydrological cycle to support the world's ecosystems (including human needs). It is estimated to be about 40,000km³. RFWR can also be calculated on a local basis for individual catchment (or otherwise defined) areas.
- **Retorting** The process of heating oil shale to produce oil, gas and spent shale.
- **Returned water** Water that was withdrawn from surface or groundwater sources, used, and then recycled, treated, discharged and disposed (see definitions that follow).
- **Reused water** Used water and wastewater that is used again before discharge for final treatment and/ or discharge to the environment. Reuse includes wastewater used for irrigation within a facility boundary. It also includes harvesting of rainwater within a facility boundary^[4].
- **Recycled water** Water that undergoes significant treatment (to reduce salinity and/or other contaminants), such that the water quality is sufficient for other uses that require fresh or near-fresh water.
- **Run-of-mine (ROM) coal** Coal straight from the mine, containing rocks and other impurities.
- S-GEM (System-level Generic Model) A modelling method used to estimate water use in complex systems such as power stations. In this handbook, S-GEM refers to the model developed by MIT for thermoelectric power.
- **Saline water** Salty water (such as seawater), with total dissolved solids in the range of 10,000–35,000mg/litre^[3].
- **Sedimentary** Sedimentary rocks are formed by the deposition of materials derived from pre-existing rocks and can also include material of organic origin. Most oil and gas reservoirs are formed of sedimentary rocks.
- **Shale gas** Natural gas trapped in fine-grained sedimentary rocks (shales) with extremely low permeability (lower than in tight gas reserves, see Tight gas).
- **Smelting** The industrial process by which a metal is extracted from its ore by the action of heat.
- **Syngas (synthesis gas)** A mixture of carbon monoxide and hydrogen (can also contain carbon dioxide).
- **Tailings pond** A place where mining residues are deposited for the solids to settle out. The fluids should be recycled, evaporated or treated before discharge.
- **Tight gas** Gas contained within a reservoir rock whose pore spaces are poorly connected (i.e. having low permeability).

- **Tight oil** Oil trapped in fine-grained sedimentary rocks, often shales, with extremely low permeability. Also known as shale oil.
- **Toe-to-heel air injection (THAI)** A combustion technology used to recover heavy oil from oil sands. Part of the oil in the reservoir is combusted by injecting air and an accelerant. The combustion front moves through the reservoir (from 'toe' to 'heel'), heating the remaining oil and reducing its viscosity so it can be pumped to the surface.
- **Transpiration** The process by which plants take up water from the soil through their roots and up through the stem to the leaves where it evaporates via the stomata (pores in the leaf surface) as they open to allow the uptake of carbon dioxide from the air. This water pathway is known as the transpiration stream. Although water is consumed in photosynthesis to produce carbohydrates, the amount transpired typically represents >99% of that taken up by the roots.
- **Vapour pressure deficit (VPD)** The difference in the partial pressure of water vapour between the saturated internal air space of plant leaves and the surrounding air. VPD is measured in kPa (thousands of Pascals).
- **Water consumption** Water that has been withdrawn but not returned to the surface or groundwater in the same drainage basin from which it was abstracted.
- **Water discharge** Water effluents, treated to meet local standards, discharged outside a reporting organization boundary to subsurface waters, surface waters, sewers that lead to rivers, oceans, lakes, wetlands, treatment facilities and groundwater.
- Water disposal Water that cannot be economically treated to meet regulatory standards for discharge into surface water bodies, and that must therefore be disposed of using some combination of evaporation and injection into disposal wells.
- **Water intensity** The volume of fresh water per unit of energy developed, expressed in cubic metres per terajoule (m³/TJ). This can apply to withdrawal or consumption intensity.
- **Water scarcity**^[5] Long-term water imbalances, combining low water availability with a level of water demand exceeding the supply capacity of the natural system.

Water stress

- Occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Standard definitions for water stress levels are:
- 1 Abundant indicates the annual renewable water supply per person exceeds $4,000 \text{ m}^3/\text{year}$.
- 2 Sufficient indicates the annual renewable water supply per person is between 1,700 and 4,000m³/year.
- 3 Stress indicates the annual renewable water supply per person is between 1,000 and 1,700m³/year.
- 4 Scarce indicates the annual renewable water supply per person is between 500 and 1,000m³/year.
- 5 Extreme Scarcity indicates the annual renewable water supply per person is less than 500m³/year^[6].

Water quality

Defined by the amount of total dissolved solids (TDS). The guidelines for drinking water, from the World Health Organisation (WHO)^[3], are compared to commonly accepted TDS levels for non-potable water^[7].

Categorization Total dissolved solids (TDS) (mg/litre)						
Fresh water	Potable or drinking water ^{[3} Excellent Good Fair Poor Unacceptable	<pre>3] < 1,500 < 300 300-600 600-900 900-1200 > 1,200</pre>				
Brackish		1,000–10,000				
Saline		10,000–35,000				
Brines		> 35,000				

- **Watershed** In hydrological terms, a catchment area sometimes called a drainage basin or watershed is the area from which the water for a single river system is drawn. Catchment areas are separated from each other by higher ground.
- **Water table** The level below which the ground is saturated with water.
- Water-use efficiency (WUE) At the level of the leaf, the ratio of CO_2 molecules assimilated to water molecules transpired. At a crop level, WUE is defined as the ratio of the crop yield mass to the mass of water evapotranspired over the growing season.
- Water use The amount of water used by a process or industrial plant. If the process includes recycling stages, water use can be higher than water withdrawal.
- Water withdrawal Water extracted from a source for use including domestic, industrial, energy-related or agricultural use. Water withdrawals are classified as either surface (from rivers, lakes or reservoirs) or groundwater withdrawals. Withdrawn water may be returned to the source, recycled, evaporated to atmosphere, disposed in a storage site for conataminated water, or embodied in a product, so water withdrawal is not necessarily the same as water consumption.

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Water in the energy industry An introduction

Water in the energy industry – An introduction is a timely study of where and how energy connects to water. Drawing together research from the Massachusetts Institute of Technology, the University of Texas at Austin, the University of Illinois at Urbana-Champaign, Tsinghua University and the University of Cambridge, it enables a better understanding of the challenges and opportunities for water-energy interactions.

This study emphasizes the need to distinguish carefully between water withdrawal and consumption, between water for energy extraction and for power production, and between different levels of water quality used in energy processes. It is a valuable guide for policy makers, businesses and academics on the technology and governance choices available for sustainable and responsible water use for energy.

Water in the energy industry - An introduction shows:

- How extractive industries are developing ways to reduce freshwater requirements.
- How the majority of water withdrawn for power production is not consumed.
- Why it is vital to distinguish where fresh water is or can be reused or replaced with lower-quality water.
- How best practice technologies and processes can greatly reduce the need for water in refineries and conversion plants.
- How regionally responsible practices in biofuel crop production can greatly reduce irrigation demands.
- Why understanding the energy requirements for the supply and treatment of water helps us to make better choices.

Supported by BP, as part of the multi-partner Energy Sustainability Challenge, which explores the implications for the energy industry of competing demands for water, land and minerals.

