Water and Energy

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Abstract

The fundamental concepts in the field of water-energy systems and their historical evolution with emphasis on recent developments are reviewed. Initially, a brief history of the relation of water and energy is presented, and the concept of the water-energy nexus in the 21th century is introduced. The investigation of the relationship between water and energy shows that this relationship comprises both conflicting and synergistic elements. Hydropower is identified as the major industry of the sector and its role in addressing modern energy challenges by means of integrated water-energy management is highlighted. Thus, the modelling steps of designing and operating a hydropower system are reviewed, followed by an analysis of theory and physics behind energy hydraulics. The key concept of uncertainty, which characterises all types of renewable energy, is also presented in the context of the design and management of water-energy systems. Subsequently, environmental considerations and impacts of using water for energy generation are discussed, followed by a summary of the developments in the emerging field of maritime energy. Finally, present challenges and possible future directions are presented.

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20.1 Introduction

20.1.1 A Brief History of Water and Energy

From the dawn of humanity, people had to ensure access to water and food for their survival. Solar energy was nourishing the Earth, triggering the hydrologic cycle, supporting the production of vegetation via photosynthesis and offering humans light and warmth during sunny days. At these early periods humans were mainly gatherers, as they collected water from its natural sources (rivers, lakes and springs) and consumed raw fruits gathered from local flora. Gradually, they utilized stone, wood and animal's bones to make tools and weapons that improved the efficiency of hunting. As they were yet unable to produce energy from other sources, they used the energy of their own bodies and muscles, acquired from food and water via metabolism, for all their activities.

Exploitation of natural resources to control the energy production, where term "production" is used as shorthand for transformation to a usable form or release from a stored form, was essential for humankind throughout its existence. Although water and food were the two basic requirements for survival, energy was essential to (a) ensure the supply of water and production of food and (b) support domestic, manufacturing and transportation activities of developing human societies.

When humans controlled fire (about 70 000–100 000 years ago), they had managed to exploit fuels for energy production for the first time. Wood was the first fuel

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used and, practically, remained the main one until the twentieth century, despite the increased use of coal from the eighteenth century. Fire changed the style and quality of life, as it provided warmth, light, a better diet (cooked or grilled meals) and protection from wild animals. Fire also triggered human development, as people gained a small amount of control over nature and extended their activities. They could now harden primitive wooden tools and weapons, work during nights, inhabit dark places (caves) and finally migrate from Eastern Africa to areas with colder climates as Europe and Asia.

At some point during the late Neolithic period, a new human activity emerged, agriculture. People shifted from gathering and hunting activities, characterized by high insecurity, to agriculture in stable fields that improved food safety. This change, known as the Neolithic Revolution (McClellan and Dorn 2015), started at about the 10th millennium BC. Somewhere around this period groups of people concentrated in a zone of hills extended from what is today Syria to the foot of Taurus and Zagros mountains, an area known as the Fertile Crescent. In this area the winter rainfalls favoured the natural growth of wild cereals, such as barley and wheat. These early communities organized cultivations, developed the first agricultural methods, domesticated animals, and constructed the first small scale hydraulic works for water exploitation. During the 8th to 5th millennium BC, the population began to increase and spread to the nearby river alluvial valleys (Nile, Tigris, Euphrates, Indus and Yellow river). The growth of agricultural activity at the new areas caused a significant increase of the water needs. However, the water was abundant and ensured by the nearby large rivers. These were the valleys where the first cities rose during the period known as Urban Revolution, offering a more civilized life to these early societies. Domestic water use, irrigation for food production and flood protection became essential for these developing civilizations. Large scale hydraulic works were constructed for collecting, transferring and storing water, as well as for urban and rural drainage (Angelakis et al. 2012; Bazza 2007). The main source of energy that supported this extended agricultural activity (planting and ploughing, transporting crops, manufacturing, lifting water from wells or rivers) remained the chemical energy utilized through human and animal muscles. The first device for lifting water was shaduf, a long wooden pole that operates like a seesaw. Its use is widespread in Mesopotamia and Egypt from 5th millennium BC until today.

As civilizations developed, a new energy source came into use, the wind. Sails on boats were possibly used for the first time around 10th millennium BC, but as the technology was improved, marine transportation expanded further to support commerce. As the use of continental roads for the transportation of goods and people was hard, ships with sails opened up new maritime trade routes. On the other hand, sailors could not control wind energy to sail against the wind and thus they also had to paddle. The technology to sail into the wind was optimized and spread several centuries later.

As metallurgical activity expanded, energy needs were substantially increased. Although Neolithic societies used soft metals such as gold, silver, lead and copper, gradually they discovered harder metals or alloys to produce tougher tools and weapons. For example, the production around the 3th millennium BC of bronze, a hard alloy of copper and tin, improved the metal industry significantly. The melting of metals consumed large amounts of thermal energy produced exclusively from wood burning. During the Iron Age around the 3th millennium BC, the need to melt harder metals, such as iron, led to production of charcoal, a partially new and artificial fuel that is widely used even today. Charcoal was made by burning wood in a low oxygen environment, a process that lasted a few days. As charcoal contains more carbon, it produces higher and steadier temperatures, than wood.

Coal, oil, natural gas and their calorific attributes were known in antiquity, but their use as fuels was quite limited. Coal was used as a fuel in a consistent way from 4th millennium BC in modern day Mongolia and China (Dodson et al. 2014). It is also mentioned by Theophrastus (4th century BC) in his treatise *On Stones*. He says that “anthrax” (Greek word for coal) was excavated from the ground, was burned like charcoal and was used for heating by copper workers. Coal was also used extensively in Roman Britain, where several exposed coalfields were exploited. It was transported to distant sites, such as London, although wood and charcoal remained the main fuels (Dearne and Branigan 1995).

Petroleum is mentioned by Herodotus (5th century BC) and Plutarch (1th century AD). Herodotus (Book 6, 119) describes wells near Susa (today central Turkey) which were used to extract “oil”; it was black with strong smell and was stored in vessels. From the same wells asphalt was extracted. In another Herodotus’ book (Book 4,185) the presence of asphalt in the Island of Zakynthos is described. Plutarch (*Parallel Lives, Life of Alexander, 35*) describes a chasm of fire at Ecbatana (today Iran) that streamed as a spring, while the abundant liquid *naphtha* was stored nearby. He mentions that naphtha was like asphalt but more flammable. Also, Plutarch narrates that “barbarians” impressed Alexander the Great by lighting the road that led to his lodging. Generally, the use of petroleum as fuel in antiquity was rare. On the other hand, the use of asphalt was widespread in almost all civilizations as waterproof material, mainly in vessels but also as mortar in buildings and pottery.

In several ancient sources, seeps from which gas escapes are mentioned. Several oil and natural gas seeps, especially in the Mediterranean area, are cited by Pliny the Elder (1th century AD) in his treatise *History of Nature*. The temple of Hephaestus, the Greek god of fire, was built next to such a burning gas seep in Chimaera, in modern day Turkey (Etiope 2015).

From the Iron Age to the Industrial revolution during the 18th century AD, most things related to water and energy management, remained almost stagnant. Wood, charcoal and wind were the main energy sources, and surface and ground water were the main water resources. As water and energy management followed the ups and downs of civilizations, few essential developments were achieved as summarized below:

(a) *Devices and mechanisms for lifting water*. Several devices were used throughout history for lifting water, as comprehensively reviewed by Yannopoulos et al. (2015). The most important, Archimedes' screw and Noria, were invented around 3th century BC. Archimedes' screw was the predecessor of the modern pump, and it was powered by human or animal force. The modern version of this device, powered by thermal or electric energy, is used in many contemporary water projects. Noria is also a very important invention, as the machine worked with hydraulic power. It is a wooden waterwheel, powered by flowing water and fitted with buckets that lifted water to another collector out of the river. Finally, it is worth to mention that the inverted siphon technology was achieved at a rather large scale in some ancient aqueducts starting from the Hellenistic period, even though this is not actually lifting of water.

(b) *Construction of hydraulic works*. All civilizations constructed extensive hydraulic works to manage water, such as aqueducts, cisterns, qanats, tunnels and dams (Angelakis et al. 2006, 2013; Feo et al. 2013). Other kinds of hydraulic works were also built with the purpose of draining cultivation areas, flood protection and river navigation. Especially, Mediterranean civilizations, that flourished in an environment of water scarcity, exploited available water resources extensively and built admirable hydraulic works.

(c) *Water use for energy production*. During the 1th millennium BC, water mills were invented to grind the grain and olives for flour and olive oil production, respectively. Olive oil became the main fuel for home lighting for several centuries and was used in most civilizations (in specific areas animal fat was used instead). Around the 7th century AD wind mills were invented in Persia, and they were used until the twentieth century all over the world to grind cereal, pump water and even drain land, like, for example, in the Netherlands.

(d) *Birth of science for understanding and control of natural powers*. As societies became more and more dependent on the natural resources, early scientists tried to understand the relevant environmental processes and describe their laws. Nature was now more predictable and hence more controllable. The first scientific theories of natural phenomena were formulated around the 6th century BC by Greek philosophers from Ionia (Koutsoyiannis et al. 2007). During the next centuries Greeks advanced the existing knowledge and defined the scientific method. Aristotle (4th century BC) codified the existing information for several natural sciences. Also he defined the way to understand nature, introduced the formal study of logic and, in particular, the methods of deduction and induction. It is worth mentioning that Aristotle first distinguished the terms energy (ενέργεια) and power (or "potential"; δύναμις) with the former being the existence of something and the latter is the potential to be something (Metaphysics Book 9, 1048a). Thus, in the context of the Aristotelian philosophy, energy is regarded as the action needed to materialize a potentiality. During this period there was significant progress in mathematics, physics, astronomy and technology. A fascinating technological achievement was the use of steam for production of mechanical motion that was discovered during 2th century BC by Heron in Alexandria. Although the invention was applied in the construction of a few amusing mechanisms, it was more than 2000 years later that the reinvented stream engine would start to play an important role in human development.

At the beginning of the 18th century, societies remained rural, and the majority of the population was involved in agriculture. The manufacturing activity was limited to small factories, cottages and urban craft shops. At the middle of the 18th century, a transition from manual labour manufacture to centralized, standardized and organized production was made. The Industrial Revolution began in England and spread to the rest of Europe and North America. In about one century, the factory system was developed, machines and tools were invented, and iron, chemical, shipping and textile industries were blooming. As wood and charcoal were the main fuels used in these developments, large quantities of wood were consumed very quickly and forests were depleted. A new fuel was used to replace wood, coal and its processed form, coke (charred coal). As coal consumption increased, surface deposits were exhausted, and deep mines were constructed. Deep galleries were flooded by groundwater, which was a big problem. The problem was resolved by an engine, called the "Miner's Friend", which replaced traditional animal-driven pumps. This pump was a great invention as it used thermal energy to convert water to steam, which under pressure produced mechanical work to remove water from mines. Later in 18th century more advanced steam engines were produced and were used in several industrial applications. However, the most important application of steam engines was in the transportation sector. During this period trains and ships moved using coal and wood as fuels.

Also, during the Industrial Revolution, the use of hydropower for industrial activities begun. Iron waterwheels were built, and water powered devices operated a variety of industrial applications, mainly in the textile industry.

At the end of the 19th century internal combustion engines which used petroleum and gas were invented. During the 20th century most human activities expanded thanks to these engines. The transportation sector in particular boomed, as cars, aircrafts and boats were now used extensively to transport people and goods. Petroleum and its derivatives, such as gasoline, kerosene and, diesel, were the main fuels for this activity, while natural gas was also available but less frequently used. During the early 20th century, the gas that was released during petroleum mining was usually burned at the fields, as it was considered very expensive to transport or to store for later use. Very soon, devices were invented to exploit gas, e.g., for heating and cooking in the domestic sector. At the end of the 20th century natural gas was already exploited extensively. Finally, the liquefied natural gas (LNG) is another common method used to facilitate conveyance.

While phenomena connected with electricity had been known since antiquity, in the 19th century a steady stream of inventions led to a multitude of practical applications, and by the end of that century electricity had transformed the world. Electricity could now be stored, transported, and transformed into other types of energy with relative ease. This led to rapid growth of the type and number of everyday life applications. During the 20th century electricity transmission networks were installed all over the Earth. In 1980 the electrical energy corresponded to 30% of the total energy consumed, and in 2015 this percentage was about 40%. Water power was one of the first resources (alongside coal and petroleum) that were used for electricity production. As electric energy needs expanded, hydropower became of great importance, and thousands of hydroelectric power plants were constructed all over the world. Their reservoirs were not only used to manage energy production but also to provide irrigation water, domestic water supply, and flood protection. In the 1950s, when the controversial nuclear technology emerged, it began to be used extensively for electricity production, using radioactive fuels such as uranium and plutonium. After the oil crisis of 1970s, societies started to explore renewable resources for electric energy generation. At the beginning of the 21th century, wind, geothermic fields, biomass, and solar energy began to be used more extensively for electricity generation.

The 20th century is also characterized by the improvement of water facilities and new related technologies, as well as the introduction of environmental protection in water management. Hydraulic works were constructed mainly for (a) collecting, transferring and distributing water from sources to end users, (b) storing water for later use, (c) cleaning potable water and managing waste waters, (d) exploiting hydropower for electricity, (e) protecting from floods, and (f) ensuring river navigation. At the end of the century, desalination plants were constructed in coastal areas, and the terms “waste water recycling” and “environmental flow” were introduced.

Table 20.1 lists some of the most important historical events that influenced water and energy management.

20.1.2 Water and Energy at the Beginning of the 21th Century

At the beginning of the 21th century, the world population exceeded 6 billion (while in 2019 it exceeded 7.7 billion) distributed among about 200 countries. In 2014 and 2015 the mean annual water consumption and energy production per capita were estimated to about 550 m^3 and 25 MWh, respectively. During the 20th century enormous infrastructures were constructed to ensure access to water, energy and sanitation to the majority of the world population. The progress of science and technology improved the design, operation and management of hydraulic works and power plants. On the other hand, many developing countries still lack these basic facilities. In Fig. 20.1 the percentage of the population that has access to potable water, electricity, and sanitation in the years 2000 and 2014 is depicted for each country.

From Fig. 20.1a-left, referring to the access to potable water in 2000, it is evident that in several countries all over the world a significant (more than 10%) percentage of the population had no access to potable water. The problem was more severe in some African countries where the majority of the population had no access to water. Regarding access to electricity (Fig. 20.1b-left) and sanitation facilities (Fig. 20.1c-left), the situation seems even worse. It is evident that several African and Asian countries had serious difficulties in covering these basic needs.

From the right panels of Fig. 20.1, which refer to 2014, it becomes obvious that during 21th century the living standards in many of these countries did not change drastically. Some improvement is visible in potable water access, but better access to electricity would help with both potable water and sanitation, overall there is a long way ahead for humanity to ensure decent living conditions for all.

Table 20.1 Milestones of water–energy use

Time (approximately)	Era	Inventions	Energy sources	Water management
100th millennium BC	Palaeolithic	Fire control	Wood	Use from sources
10th millennium BC	Neolithic revolution	Agriculture, Animal domestication, Sailing	Wind	Water transfer, Water storage
5th millennium BC	Urban revolution			Urban water supply
1th millennium BC	Iron age	Charcoal production	Charcoal	Recreational use, Advanced hydraulic works
5th century BC		Pumping devices, Water mills	Water	Water lift, Scientific explanations for geophysical processes
7th century AD		Wind mills	Wind	River navigation
18th century	Industrial revolution	Steam engine	Coal	Industrial water uses
19th century	Scientific revolution	Internal combustion engine	Petroleum, Natural Gas	
20th century		Electricity, Nuclear Energy	Water, Nuclear fuels, Geothermic, Solar, Marine	Desalination, Recycling, Environmental flow

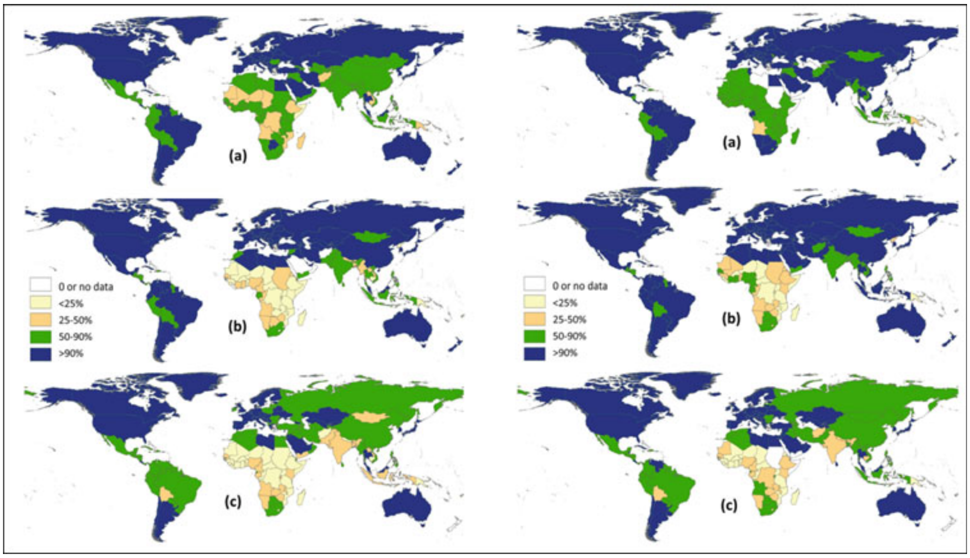


Fig. 20.1 Access to **a** potable water, **b** electricity and **c** sanitation (% of the population of each county) in the year 2000 (**left**) and 2014 (**right**) (constructed from data of World Bank; https://data.worldbank.org/)

20.1.2.1 Water Use

According to World Bank data for 2014, the world's annual water consumption was estimated to about 4000 km^3; this corresponds to about 550 m^3 per person. Five countries (India, China, USA, Pakistan and Indonesia), whose population amounts to 30% of the global, were responsible for more than 60% of the total global water consumption. From the total amount, 70% was used for irrigation, 19% for industrial, and 11% for domestic use (a mean value of 170 L/d per person). These uses are classified as consumptive, as water is removed from its initial environment or its quality degrades to a state that it requires treatment for reuse. The water consumption quantities are estimated on a country basis based on data from free web databases maintained by organizations such as the Food Agricultural Organization (FAO; https://www.fao.org/nr/water/aquastat/data/query/index.html) and the World Bank (https://data.worldbank.org/indicator).

Irrigation refers to water used to assist in growing crops, to protect plants against frost or to remove salts from the crop root zone. Industrial use refers to water used in industries for purposes such as processing, cleaning, diluting and cooling. Domestic use refers to water that is used in households for everyday needs, such as drinking water, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering gardens. In addition to the main three water uses mentioned above, there are a few more specific consumptive water uses, including (a) commercial (water for hotels, office buildings, and other commercial facilities), (b) livestock (water for stock animals, dairies, fish farms, and other nonfarm needs), and (c) mining (water for the extraction of minerals such as coal and ores, crude petroleum, and natural gas).

On the other hand, there are several non-consumptive uses, where the water remains in the natural environment. The main non-consumptive water uses are: (a) hydroelectric energy production, (b) river navigation, (c) recreational activities (fishing, sailing, swimming), and (d) preservation of the environment. The latter use includes mainly water releases from reservoirs in order to (a) help fish reproduction, (b) restore natural river flow regime, and (c) provide water to wetlands to protect their ecosystems.

To cover all these water demands, a large amount of available water resources has to be exploited by constructing the appropriate hydraulic works. Potentially, water can be found in the (a) ground (aquifers), (b) surface of the earth (rivers, lakes), (c) atmosphere (rain, water vapour) and, (d) sea (after desalination). Alternative sources could be the transfer of water from other areas or reusing the outflows of drainage networks or waste water treatment plants. The atmospheric water is exploited as a source only on a small scale mainly by harvesting rain water and humidity condensation installations such as fog collectors.

20.1.2.2 Energy Use

According to the United States Energy Information Administration data (EIA 2017) the total world primary energy production in 2017 was about 14 000 Mtoe (million tons of oil equivalent). Here one toe is the quantity of energy that is released from the combustion with 100% efficiency of a ton of crude oil; this corresponds to 41.9 GJ or 11.6 MWh. The world primary energy was mainly produced from coal, petroleum and natural gas and consumed in the industrial, transportation, domestic, and commercial sectors. The distribution of primary energy (TWh) by source and use in 2017 is shown in Fig. 20.2a. Some of the electricity used by the different sectors was originally generated from fossil fuels. Hydropower and nuclear power have a significant share in electrical energy production as well. Apart from hydropower, other renewable energy sources such as wind, (direct) solar radiation, biomass and biofuels, geothermal, and marine energy (waves, tides, currents) have a small but increasing share. Biomass and geothermal energy are widely used as thermal energy sources, especially in the industrial and domestic sectors. Notably, the conversion efficiency of fossil fuels for electricity production is generally low (35% for coal to 55% for natural gas) when compared to the conversion efficiency of hydropower (more than 85%).

The total electricity produced globally in 2017 was about 25 500 TWh (2200 Mtoe) and the consumed fuels (mostly fossil) were about 6000 Mtoe. The world electric energy mix for 2017 is presented in Fig. 20.2b. From the end of the 20th century the fear of exhausting fuel reserves combined with environmental concerns triggered an effort to increase the share of renewable energy sources in electricity production (Fig. 20.2b). Also, the technique of coproduction of thermal energy from electric power plants was widely used and increased the efficiency of the systems to more than 70%.

The industrial sector consumed 53% of the total global energy production and was proportionally fed by petroleum, coal, natural gas and electricity. The transportation sector consumed 25% of the total energy and was almost exclusively fed by petroleum. Finally, domestic and commercial

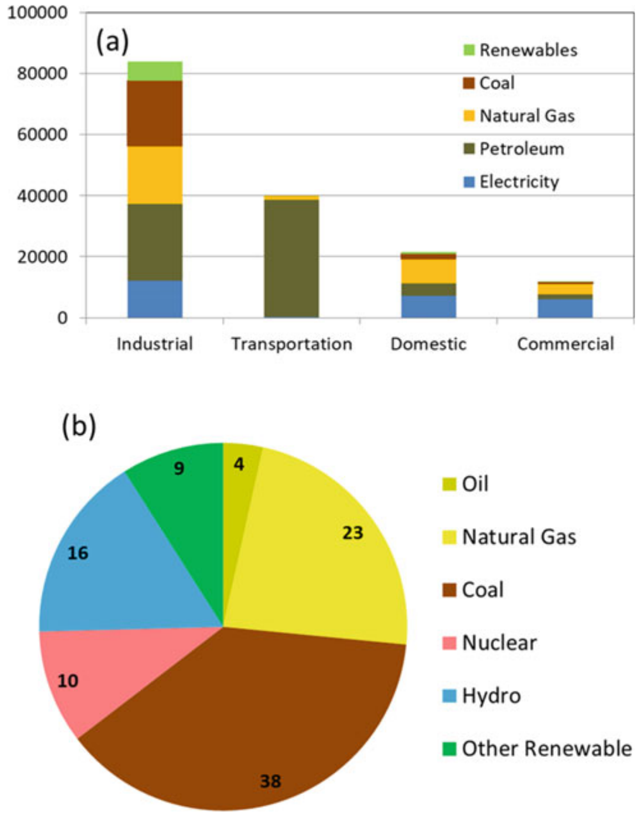


Fig. 20.2 **a** Distribution of primary energy (TWh) by source and use (constructed from data from EIA); **b** World electric energy mix for 2017 (constructed from data from BP British Petroleum 2018)

sectors consumed the 22%, and were mainly fed by electricity, natural gas and petroleum.

Fossil fuels (petroleum, natural gas and coal) produced 65% of electrical energy, while hydropower and nuclear energy were also very important for power generation as they were responsible for 26% of electrical energy production.

20.2 Water-Energy Nexus

Water and energy systems interrelate in multiple ways that are both complex and dynamic. For example, energy is used for abstracting, purifying, distributing and disposing water, while water is indispensable for various energy production phases, including, among other processes, oil drilling, biofuel production, thermal plant cooling and hydropower. Accordingly, problems with one may directly or indirectly affect the other, e.g. water shortage having negative knock-on effects on energy production. These close relationships belong to the so-called 'water-energy nexus', a term coined to describe the multiple interactions between the two systems. Some of the earliest attempts to investigate water-energy interdependencies in the economy and water sector, thus introducing a joint approach into policy planning, were made in the United States in 2006 (US DoE 2006). Langhamer et al. (2010) discussed the scientific and technological aspects of water and energy and explored related research challenges. During the first two decades of the 21th century, a growing body of research acknowledged the water-energy nexus complications and its relevance to the economy. However, the identification of these relationships and their impact remains a field largely underexplored till now.

20.2.1 Water Used for Energy Production

According to Spang et al. (2014), approximately 52 km^3 of freshwater are consumed annually for energy production, excluding hydropower (which in fact does not consume water). Yet this number is an approximate estimate coming from countries with greatly diverse economies and energy sectors. In the United States the energy sector is regarded to be the biggest consumer of water resources (Carter 2010). The U.S. is also the most important consumer on a global scale, followed by China, while for instance, northern Africa has a minimal contribution to the global amount of water used in the energy domain. Apparently, these statistics should be viewed with caution as the assumptions behind them may vary substantially, while also they are changing over the years due to reforms in the energy sector and emergence of more water-efficient technologies that reduce the pressure on regional water resources.

To trace the water used for energy production in a more systematic way, Hoekstra and Hung (2002) introduced the concept of the 'water footprint' of a country, i.e. "the volume of water needed for the production of goods and services consumed by the inhabitants of the country". The water-footprint has been further specified to denote three distinct types of water use: 'blue water', referring to consumption of groundwater and surface water; 'green water', denoting the amount of rainwater required for a product, e.g. rain-fed agriculture; and 'grey water', representing the amount of freshwater required to dilute pollutants to maintain water quality according to certain standards (Hoekstra and Chapagain 2006). This concept has also been used in energy production and supply in order to identify impact of trading relationships on water resources. For example, petroleum products heavily contribute to the water footprint for energy production in Thailand, but very little to the water footprint for energy supply, since related energy is mostly exported, while the opposite is true for the country's crude oil water footprint (Okadera et al. 2014).

It is also useful to differentiate between two types of water use for energy, i.e. 'water withdrawal' and 'water consumption'. The first denotes the amount of water removed or diverted from a source for use. The second is a part of the first and denotes the water withdrawn that is evaporated, transpired, incorporated into products or crops, or otherwise permanently removed from the immediate water environment (Kenny et al. 2009). Most relevant studies focus on water consumption.

The following sub-sections refer to operational uses of water excluding indirect uses of the life-cycle, for instance, water used in energy stations auxiliary facilities, e.g. sanitary facilities.

20.2.1.1 Fossil Fuel

Crude oil production requires water for processes including onshore oil exploration, onshore oil extraction and production, enhanced oil recovery, water injection (water-flooding), thermal steam injection, oil refining, and other plant operations. The amount of water required is regionally varied, mainly according to the combination oil recovery techniques used in each case. For example, primary oil recovery, by means of the natural pressure of the well, is much less water-intensive than secondary oil recovery, including water-flooding, whereas varied estimates are reported for enhanced oil recovery techniques such as CO_2 injection (Wu et al. 2008). Excluding enhanced oil recovery, median values of 0.081 m^3/GJ and 0.040 m^3/GJ are reported (Spang et al. 2014; Wu et al. 2008) for conventional oil extraction and refining, respectively. These estimates differ, in general, for less common crude oil production, such as oil sands and shale oil, though altogether tend to decrease over the years as energy technologies become more water efficient and employ other sources than freshwater, e.g. saline or brackish water (Wu et al. 2008).

Coal consumes water for surface or underground mining, beneficiation, slurry pipelines, and other plant operations, while natural gas requires water for the processes of onshore exploration, onshore extraction, natural gas processing, gas pipeline operation, and other plant operations. Shale gas is even more water intensive requiring water for the process of hydraulic fracturing (fracking) with estimates ranging in the United States from 1136 m^3 per well to 34 069 m^3 per well in 2012 (Meldrum et al. 2013). Reported median global estimates are 0.043 m^3/GJ, 0.004 m^3/GJ and 0.017 m^3/GJ, for coal, natural gas and shale gas production, respectively (Meldrum et al. 2013; Spang et al. 2014).

In the fossil fuel industry, water consumption is globally dominated by the oil industry where water is used for crude oil extraction and refinement processes, except for China, India, Indonesia and Australia, where coal is the greater consumer of water among the fossil fuels (Spang et al. 2014). The natural gas industry has a minor contribution in water consumption worldwide, with Russia and the United States being the major contributors.

20.2.1.2 Nuclear Fuel

Water is required for many processes involved in the production of nuclear fuel, including uranium mining, milling, conversion, enrichment, fabrication, and reprocessing phases. A median water consumption estimate of 0.105 m^3/GJ is reported for these processes (Meldrum et al. 2013; Spang et al. 2014).

On a global level, water requirements for nuclear fuel production are estimated an order of magnitude lower than that of fossil fuels (Spang et al. 2014), which is both a result of the limited availability of uranium deposits and the restricted nuclear fuel production worldwide.

20.2.1.3 Biomass Production and Processing

Biomass may refer to (a) food crops, such as sugarcane and rapeseed, (b) energy crops as poplar and miscanthus, as well as (c) various types of organic waste from agriculture processes, e.g. manure and crop-residues (Gerbens-Leenes et al. 2009). Biomass is often subsequently processed to biofuels such as biodiesel, ethanol, and biogas. For example, the United States and China produce maize-based ethanol, India uses rapeseed to produce biodiesel, and Brazil depends on sugarcane to produce ethanol. Water for biofuels relates both to the water required for the cultivation of biomass, in the case of crops, and to water required for its processing. Biofuels are mainly first-generation, including biodiesel, ethanol, and biogas, and second-generation, including energy crops and waste products.

In case of first-generation biofuel, water is primarily required for cultivation of biomass. This type of biomass production is generally considered the most water-intensive energy production process due to its dependence on irrigation. Relevant estimates are highly regionally varied and uncertain, since they heavily rely on the crop type, irrigation system, and climatic conditions (Mielke et al. 2010). Subsequently, ethanol production from biomass requires water associated to grinding, liquefaction, fermentation, separation, and drying processes (Wu et al. 2009).

Second-generation biofuels require water mostly for conversion of cellulosic ethanol to ethanol through biochemical or thermochemical processing (Naik et al. 2010). In general, second-generation biofuels do not require incremental irrigation if grown in their native ground, and water use estimates are usually omitted, though some energy crops may need additional irrigation (Wu et al. 2009).

In 2016, biofuels yielded only a small amount of the total energy production (957 TWh), according to data from BP Statistical Review of World Energy (British Petroleum 2017); however, they are a growing energy pathway (Berndes 2008). For instance, in Thailand energy from biofuels had already reached 18% of total energy supply in 2010 (Okadera et al. 2014).

20.2.1.4 Electricity

Electricity has the most diverse profile of water consumption owing to the variety of pathways for electricity production in terms of fuel, generator type, and cooling type. Spang et al. (2014) classify these in eight major categories: coal-based steam turbine (ST), gas- and oil-powered ST, nuclear ST, biomass and waste heat ST, geothermal ST, solar ST, combined cycle, and gas turbine. The majority of water used in the production of electricity refers to water used for thermoelectricity processes, i.e. freshwater used for cooling the steam after exiting the turbine generator. The cooling water that is needed by thermal power plants is estimated to be around 76–190 m^3/MWh (Kohli and Frenken 2011). Geothermal technologies differ in the usage of water due to differences in technology configurations and regional characteristics (Clark et al. 2010), and may require further water usage for generation of electricity (Macknick et al. 2012).

Hydroelectricity provides 16% of the total world electric energy production, which corresponds to 80% of renewable sources. For some countries (Albania, Norway, Paraguay and Congo), it is almost the only resource in their electric energy mix. During the twentieth century, the extensive use of hydroelectricity revealed issues of great importance to the operation of water-energy systems. Hydroelectric energy is produced by the falling of a water volume from a certain height. The main method to exploit the hydropower of a river is to build a dam that forms an upstream reservoir, which regulates river flow. At certain time periods, water is released under pressure to produce electric energy. However, allocation of water consumption for hydropower is generally avoided in the literature, since water is not actually consumed. Hydroelectric dams are usually multi-purpose works, serving simultaneously flood control and water supply purposes, so assigning, for instance, evaporation losses solely to hydropower is ambiguous and misleading.

For other electricity technologies such as photovoltaic (PV) plants and wind power production, water is mostly associated with occasional life-cycle requirements of washing PV panels and wind turbine blades. Thus these present the lowest withdrawal and consumption rates (Macknick et al. 2012), and also rank low on the global scale of water use in the energy sector (Spang et al. 2014).

20.2.2 Energy Intensity of Water Sector

At the start of the 21th century and considered on a global scale, water is an important input for nearly all forms of energy (International Energy Agency 2016). Although the water sector is not yet a significant user of energy on a global level, in light of energy reforms towards a 'greener' economy and increasing use of desalination plants, this is likely to change. Recent important developments involving the use of novel desalination methods, such as nanoporous graphene sheets as well as capacitive deionization, which are much more energy efficient compared to the reverse osmosis method, could further increase the spread of desalination plants (Aghigh et al. 2015; Copeland and Carter 2014; International Energy Agency 2016). According to the International Energy Agency (2016), the global energy consumption in the water sector reached approximately 5×10^9 GJ (1390 TWh) of energy in 2014, about 60% of which is in the form of electricity.

In the United States, past analysis has shown that over 3% of the national electricity consumption is used for water-related purposes (Cohen et al. 2004). However, these aggregate estimates do not show the large variability of the energy-intensity on the regional scale, e.g. California uses 19% of its electricity and 32% of its natural gas resources for services related to the water sector (Klein et al. 2005; Stokes and Horvath 2009).

Energy for the water supply sector has been classified into 'physical energy' (the amount of energy applied to produce and transport water supplies to meet demand within each hydrological region) and 'embedded energy' (the actual amount of energy needed in other regions to produce and deliver water that is consumed within that region). Specifically, the energy embedded in water is defined as "*the amount of energy that is used to collect, convey, treat, and distribute a unit of water to end users, and the amount of energy that is used to collect and transport used water for treatment prior to safe discharge of the effluent in accordance with regulatory rules*" (Park and Bennett 2010). The term 'energy intensity' refers to the average amount of energy used for these processes on a per unit basis.

20.2.2.1 Urban Water and Wastewater

Energy estimation for the urban water cycle can be segmented into the phases of supply, conveyance, treatment and distribution of water, and waste water treatment (Park and Bennett 2010).

The supply phase may include surface water, groundwater, desalinated water, and recycled water. Due to their increasing importance, desalination plants are examined separately below. Relevant energy consumed in the supply process is driven by the type of the source water, the technology used in each case, and the regional regulatory standards. In essence, exploitation of groundwater requires a supply of energy determined by the pumping method and efficiency, the depth of the well, and the volume of the pumped water. About 800 TWh (3% of the total world electric energy production) are required to pump water from deep aquifers (e.g. 80 m). For example, in Greece, a country where groundwater is extensively used for irrigation, 5% of total electricity was consumed in water pumping. In some agricultural regions, in which deep wells are used, this percentage is up to 15%. Recycled water's energy intensity is driven by the wastewater discharge standards and the level of additional treatment that is required in order to bring the water into an acceptable quality for the specific purpose of interest. The extraction of surface water and groundwater generally accounts for the 40% of the electricity used in the water sector (International Energy Agency 2016).

Energy intensity of water conveyance and distribution by means of pumping depends on the topography, the geometric and hydraulic properties of the pipe system, and the requirements of consumers in terms of discharge and pressure.

Energy intensity of water treatment is subject to the type of treatment technologies used, the water quality standards, the initial quality of the raw water, as well as the treatment plant configurations. For example, energy-intensive methods include reverse-osmosis, ozonation, and ultraviolet light rays.

Finally, the energy consumed in the waste water treatment plants is determined by the plant capacity, the level of treatment, the technology used, the wastewater influent quality, and the discharge standards (primary, secondary or tertiary). In 2014, it was estimated that a quarter of the electricity consumed by the water sector was used for waste water collection and treatment. This electricity demand is projected to increase by 60% or even more up to 2040, as more wastewater will be collected and treated (International Energy Agency 2016). Yet, in some cases, the use of the produced biomass from waste covers a significant part of the thermal and electric energy needed for treatment.

20.2.2.2 Agricultural Uses and Irrigation

Irrigation is a dominant consumer of energy. Energy required depends on (a) the type of source water used (surface water or pumped groundwater), (b) the type of irrigation methods (surface, drips, sprinklers), and (c) the water requirements of the crop. In South Asia, and particularly in India, irrigation heavily depends on groundwater pumping and is energy-intensive to such a degree that it is frequently described by the term the 'energy-irrigation nexus' (Shah et al. 2004).

In the first decades of the 21th century, alternative sources to produce electricity for irrigation have been explored. For instance, renewable resources, especially photovoltaic panels, are used to produce energy for pumping (Chandel et al. 2015).

20.2.2.3 Desalination Plants

Desalination refers to the process of converting non-usable water resources into usable by removing excess salts and minerals. The energy intensity depends on the volume of water being desalinated, the quality of the source water, and the specific desalination technology. For example, processing brackish water, containing moderate amounts of salts and minerals, is not as energy-intensive as processing sea water, containing very high quantities of salts and minerals. Desalination technologies utilize either thermal energy, e.g. in multi-stage flash systems, or mechanical energy as in reverse osmosis, the most commonly installed technology (International Energy Agency 2016). The reduction of energy-intensity of water desalination technologies is a very active research field with reverse-osmosis desalination plants showing the most growth and concentrating engineering focus worldwide (Peñate and García-Rodríguez 2011), while new graphene-based technologies also have a great potential (Aghigh et al. 2015). It is highly likely that in the future desalination will be a viable alternative to mitigate water scarcity due to limited water resources or during drought periods. Although desalination is a very energy consuming process (3.5–5 kWh/m^3 for reverse osmosis), the resulting world energy demand is low. The desalination plants have a global annual water production of about 6 km^3 and consume about 30 TWh of energy, a value that corresponds to the 0.1% of total electricity production (see FAO database mentioned above). Desalination processes accounted for roughly 5% of the electricity used in the water sector in 2014 (International Energy Agency 2016), and it is projected to rise to more than 20% in 2040.

20.2.3 Synergies and Trade-offs

The various interdependencies of the water-energy systems often lead to competitive uses of the naturally constrained resources, thus rendering the management of these systems challenging. The competitive nature of the resources may have detrimental effects on the economy and water sector if ignored in the management strategy, while, on the other hand, an integrated approach creates opportunities for mutually beneficial situations.

McCornick et al. (2008) reviewed interesting case studies; among them the case of Ethiopia. In spite of water abundance and great hydropower potential, Ethiopia lacks relevant infrastructure and is very dependent on unsustainable biomass growth, leading to poverty, water insecurity, energy deficiency and destruction of forests, among others. The use of hydropower dams as a means for integrated management of water-energy systems has long been advocated (Koutsoyiannis et al. 2003, 2009; Nalbantis and Koutsoyiannis 1997) with an emphasis on the necessity of large scale projects to increase energy-efficiency and enable reliable multi-purpose operation (Koutsoyiannis 2011a; Koutsoyiannis et al. 2003; Nalbantis and Koutsoyiannis 1997).

At the beginning of the 21th century, environmental or climate concerns and efforts to reduce economy's dependence on fossil fuels engendered an increase in the use of renewable resources, including biomass. However, these policies, being highly dependent on existing water and land resources, have sometimes been criticized of disregarding the latter, placing pressures on stressed water resources and leading to land degradation, and thus having opposite effects to the ones intended (Pittock 2011). Concerns about the shift towards biomass have also been expressed due to substitution of water and land resources from food production to energy production, i.e. a 'water for food' versus a 'water for energy' competition (Dalla Marta et al. 2011; Gerbens-Leenes et al. 2009).

Eventually, we should be able to increase efficiency in both sectors and achieve water and energy security by better informed integrated policies together with technological innovations. An important reflection on the regional nature of the water-energy stresses and on the limits of future progress is provided by Bazilian et al. (2010, 2011). The study notes that arising inequalities in terms of present and future access to water and energy should be examined in political terms as well as in terms of environmental and technological constraints, and therefore, political prioritization is also required.

20.3 Energy Hydraulics

20.3.1 Governing Equations

In order to extract energy from water or to add energy to water, we use *hydrodynamic machines* called *turbines* and *pumps*, respectively.

The governing equation for electric power production via transformation of the dynamic and kinetic energy of water is

$$P = \eta \rho g Q H_n \tag{20.1}$$

where ρ is the water density with a typical value for clean water of 1000 kg/m^3; g is the gravity acceleration with a typical value of 9.81 m/s^2; Q is the discharge; H_n is the *net* or *effective head*, i.e. the dynamic energy, expressed as elevation difference, after subtracting the hydraulic losses across the water transferred to the turbine, which depend on Q; and η is the turbine efficiency that changes with Q, according to a function which is a characteristic of the turbine. Both H_n and Q may vary in time, and therefore so does P. By applying the SI units for Q (m^3/s) and H_n (m), the power P is expressed in Joules per second (J/s) or Watts (W).

Similarly, the governing equation for estimating the power consumed by lifting water at head H_m through pumping is given by

$$P = \rho g Q H_\mathrm{m}/\eta \tag{20.2}$$

where H_m is the so-called *manometric head*, and η is the pump efficiency, which is a function of Q that is a characteristic of the pump. The manometric head is the sum of the elevation difference Δz plus the hydraulic losses across the pipeline system, where $\Delta z = z_2 - z_1$, with z_1 and z_2 being water elevations before and after the pump (typically $z_1 < z_2$).

The energy produced or consumed during a time interval $[t_1, t_2]$ is the integral of P, i.e.

$$E = \int_{t_1}^{t_2} P(t)dt \tag{20.3}$$

After simplifications, we get the following formula, expressing the average energy produced over a specific time interval

$$E = \rho g V \overline{H}_\mathrm{n} \overline{\eta} \tag{20.4}$$

where V is the water volume that passes through the turbines during the time interval $[t_1, t_2]$, and $\overline{H}_\mathrm{n}$ and $\overline{\eta}$ are the net head and efficiency during this period, respectively, averaged over time.

Similarly, the consumed energy over a specific time interval due to pumping is approximated by

$$E = \rho g V \overline{H}_\mathrm{m}/\overline{\eta} \tag{20.5}$$

where the symbols have the same meaning as above.

20.3.2 Key Concepts of Hydropower Technology

Hydropower is generally produced either through *hydroelectric dams* or *run-of-river plants*. The former take advantage of the height difference that is artificially generated due to the rise of the river level upstream of the dam, and they also take advantage of the regulation capacity of the reservoir, which allows for storing the surplus flows and releasing them according to the time-schedule imposed by the reservoir management policy. On the other hand, run-of-river plants do not have significant storage capacity, and thus they operate with the available natural flow, which is irregularly varying. There are also other types of hydropower plants which make use of wave and tidal energy, but they are based on the same energy transformation laws.

Figure 20.3 illustrates a sketch of a conventional hydroelectric work, comprising the *dam*, the *intake* system, the conveyance pipe, called *penstock*, the turbine station, the outflow pipe, called *draft tube*, and the channel conveying water to the river, called *tailrace*. The dynamic energy of water is expressed by means of the so-called *gross head*, which is determined by the reservoir level upstream z_1, and the outflow level downstream z_2, i.e. $H = z_1 - z_2$. The reservoir level ranges between a minimum and a maximum value, i.e. the intake level and the spill level, respectively. The outflow level may also vary (e.g., outflow to a river), yet its fluctuation is generally very small, if compared to the variability of the upstream level, thus it is usually neglected in computations.

As the flow is conveyed from upstream to downstream, the available dynamic energy is decreased due to frictional and local energy losses that occur along the flow conveyance from the intake to the turbine. Therefore, the available energy to be converted, expressed by means of kinetic and pressure energy, is reduced by the quantity of losses ($\Delta H = H - H_n$), while the amount of mechanical energy that is finally available as electric power is further reduced by the factor $1-\eta$.

Key design objective is to minimize the hydraulic losses and maximize the turbine efficiency in order to exploit as much of the gross head as possible. The overall design of the hydropower system is in fact a challenging optimization problem, involving the construction and maintenance costs of hydraulic and power infrastructures, and the benefits of energy production. Typically, conventional large-scale hydropower systems exploit 80–85% of the gross head, where 3–10% of head reduction is due to hydraulic losses and about 10% to conversion losses.

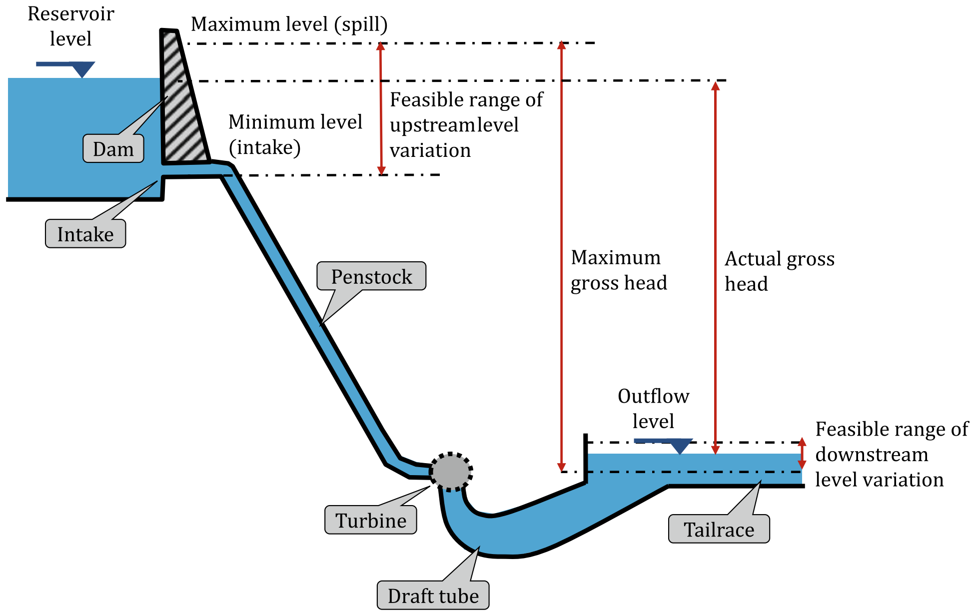


Fig. 20.3 Sketch of a conventional hydropower system

20.3.3 Hydraulic Losses

Frictional losses across the penstock as well as local energy losses that occur due to the changes in the flow geometry contribute to gross head reduction.

For given discharge Q and pipe diameter D, the flow velocity is given by

$$V = \frac{4Q}{\pi D^2} \tag{20.6}$$

For the above flow characteristics, the energy gradient J across the pipe is typically estimated by the so-called Darcy-Weisbach formula

$$J = f \frac{1}{D} \frac{V^2}{2g} \tag{20.7}$$

where f is a (dimensionless) friction factor. The latter is given by the Colebrook–White equation

$$\frac{1}{\sqrt{f}} = -2 \log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \tag{20.8}$$

where $\mathrm{Re} \coloneqq V\,D/\nu$ is the *Reynolds number* and ε/D is the *relative roughness*, both dimensionless, whereas ε is the absolute (surface) roughness of the specific pipe and ν is the kinematic viscosity of water, which is function of temperature; e.g., for $T = 15$ °C, $\nu = 1.1 \times 10^{-6}$ m^2/s.

For a pipe of length L *and diameter* D, assuming steady uniform flow with discharge Q, the *friction losses* h_{f}, which are the main component of the total hydraulic losses, are given by

$$h_{\mathrm{f}} = fL \frac{8Q^2}{\pi g D^5} \tag{20.9}$$

Due to the complexity of friction loss calculations based on (20.6), a number of simplified formulas have been developed in the literature (e.g., the Hazen-Williams expression), which are however noticeably less accurate than the Darcy-Weisbach equation. A more consistent and accurate approximation is offered by the so-called *generalized Manning equation*, introduced by Koutsoyiannis (2008):

$$J = \left(\frac{4^{3+\beta} \mathrm{N}^2 Q^2}{\pi^2 D^{5+\beta}}\right)^{1/(1+\gamma)} \tag{20.10}$$

where β, γ and N are coefficients depending on roughness, for which Koutsoyiannis (2008) provides analytical expressions that are valid for specific velocity and diameter ranges. In particular, for the large diameters (i.e., $D > 1$ m) and velocities (i.e., $V > 1$ m/s) that are typically applied in hydropower systems, we get:

$$\beta = 0.25 + 0.0006\varepsilon_* + \frac{0.024}{1 + 7.2\varepsilon_*}, \gamma = \frac{0.083}{1 + 0.42\varepsilon_*},$$
$$\mathrm{N} = 0.00757(1 + 2.47\varepsilon_*)^{0.14} \tag{20.11}$$

where $\varepsilon_* := \varepsilon_0$ is the so-called normalized roughness and $\varepsilon_0 := \left(\nu^2/g\right)^{1/3} = 0.05$ mm, for temperature 15 °C.

The roughness coefficient ε is a characteristic hydraulic property of the pipe, mainly depending on the pipe material and age, where aging is mainly associated with pipe erosion due to the presence of sediments. For design purposes, it is recommended to apply quite large roughness values, e.g. $\varepsilon = 1$ mm, in order to account for all above factors at the end of time life of the penstock. For the above value, we get $\varepsilon_* = 1/0.05 = 20$, and thus $\beta = 0.262$, $\gamma = 0.009$, and $N = 0.0131$.

On the other hand, local losses, also referred to as *minor hydraulic losses*, are occurring at every change of geometry and thus change of the flow conditions (e.g. flow entrance through the intake, change of diameter, flow split, elbow, etc.). Each individual loss is generally estimated by

$$h_\mathrm{L} = k\frac{V^2}{2g} \tag{20.12}$$

where k is a dimensionless coefficient, depending on geometry. Classical hydraulic engineering handbooks (e.g., Roberson et al. 1998) provide analytical relationships, empirical formulas and nomographs for estimating k as function of local geometrical characteristics (e.g., ratio of upstream to downstream diameter). Typical values that are applied in hydroelectrical system components moving from upstream to downstream are:

- $k = 0.04$ for intakes;
- $k = 0.10$–0.15 for grates;
- $k = 0.08$ for contractions;
- $k = 0.10$ for elbows;
- $k = 0.10$–0.20 for fully open valves;
- $k = 1$ for outflow to the tailrace.

In preliminary design studies, local loss calculations are generally omitted, since the geometrical details are not yet specified, or they are roughly estimated, by considering an aggregate value of k for all types of local losses.

20.3.4 Turbines

A hydraulic turbine (from the Latin *turba*, meaning vortex, transliteration of the Greek *τύρβη*, meaning turbulence) is a rotary mechanical structure that converts the available kinetic and pressure energy of water (i.e. the net head) into mechanical work, which is next used for generating electrical power, when combined with a *generator*. Early turbine examples are waterwheels and windmills.

In large hydroelectric systems, turbines are generally classified into two categories, namely *impulse* and *reaction* (Fig. 20.4). In an impulse turbine, a jet of water passing from a contracting *nozzle* enters the curved (double) *buckets* of the turbine wheel to produce energy as the runner rotates. After impinging the buckets, the water outflows freely (i.e. under atmospheric pressure) to the downstream channel (Fig. 20.4, left). Since the jet flow is not axisymmetric, and only part of the runner is activated (typically only two or three out of a total of about 20 buckets are simultaneously hit), impulse turbines are also referred to as *partial admission*. They are also called *Pelton wheels*, in honour of the American engineer Lester Allan Pelton, who invented this machine in the 1870s (apparently by streamlining the traditional windmill technology). As shown in Fig. 20.4 (left), the objective is to convert the available dynamic energy (net head) into kinetic energy by substantially increasing the flow velocity from V_1 to V_2, where V_1 is the velocity through the penstock with diameter D_1, and V_2 is the velocity through the nozzle with diameter $D_2 << D_1$. If Q is the discharge, then from the continuity equation we get

$$Q = V_1 \pi D_1^2/4 = V_2 \pi D_2^2/4 \Rightarrow V_2 = V_1(D_1/D_2)^2 \tag{20.13}$$

Generally, V_1 ranges from 4 to 6 m/s, while V_2 may exceed 100 m/s. Impulse turbines are applied in the case of significant heads ($H > 250$ m) and relatively small discharge. Large units may have multiple impinging at different locations of the wheel.

There also exist other types of impulse turbines that are applied for low heads and large discharges, e.g. the Turgo turbine, which uses single instead of double buckets on the wheel that are shallower than the Pelton ones, and where the jet is horizontal. Another example is the cross-flow turbine (Fig. 20.5, right), in which the water passes through the turbine transversely or across the turbine blades, and after passing to the inside of the runner, it exits on the opposite side. Passing through the runner twice provides additional efficiency, and also allows for self-cleaning from small debris, leaves etc. Another advantage of cross-flow turbines is the practically flat efficiency curve under varying loads, which makes them ideal for run-of-river plants.

In contrast to impulse turbines, which operate under atmospheric pressure, in reaction turbines, the flow is under pressure, since the chamber of the runner remains completely filled by water. In this case, the runner consists of several guide vanes, which change the direction of flow, thus producing forces due to change of momentum, which in turn make the runner rotate. After leaving the runner, the water enters the draft tube, before being extracted to the tailrace. The objective of the draft tube is to convert the mechanical (hydraulic) energy into rotational energy of runner-generator system, while reducing the flow velocity and hence the kinetic energy at the outflow section, i.e. the tailrace. As shown in Fig. 20.4 (right), this energy is subtracted from the gross head, thus it is a hydraulic loss in the system.

There are two main types of reaction turbines, the so-called Francis machine, which is suitable for a wide range

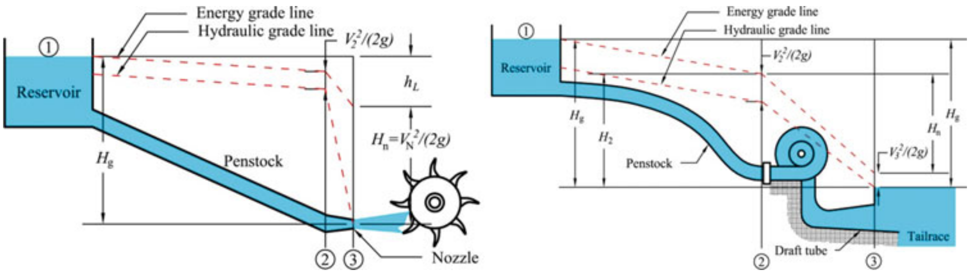


Fig. 20.4 Sketches of impulse (left) and reaction (right) turbines (adapted from Leon and Zhu (2014))

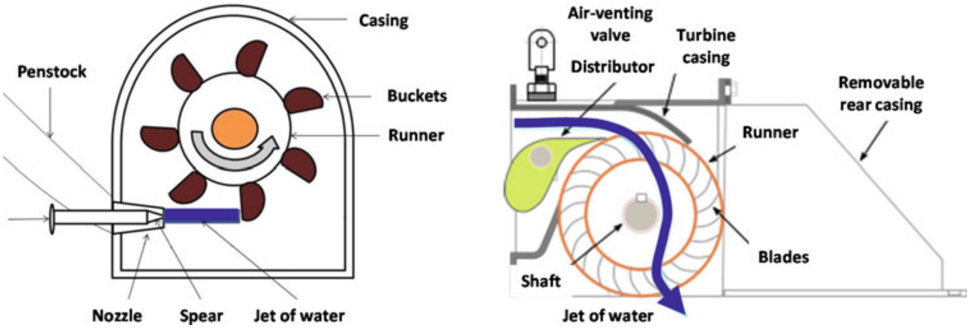


Fig. 20.5 Sketches of Pelton (left) and cross-flow (right) turbines (adapted from Wikipedia)

of discharge and head conditions (and thus applied in the majority of hydroelectric dams, worldwide), and the propeller (also known as Kaplan) turbine, which is employed in cases of high-flow and low-head power production, e.g. tidal stations.

Turbines are also classified according to the main direction of flow in the runner as tangential-flow (Pelton), radial-flow (Francis), mixed-flow (cross-flow) and axial-flow (Kaplan). The selection of the turbine type is driven by the available head and discharge. Within preliminary investigations, we may refer to nomographs, such as in Fig. 20.6. Actually, the overall design of a large-scale turbine system is a very challenging task, also requiring laboratory experiments to identify the geometrical details and assess the hydraulic performance of the specific machine. One of the most important issues to account for within design is cavitation, affecting runners in reaction turbines, in which the relative pressure at the discharge ends of the blades is negative (Novak et al. 2006).

Since the flow conditions differ across different turbine types (e.g., atmospheric pressure for impulse turbines, pressurized flow for reaction turbines) and their geometrical details also differ, the turbine characteristics affect the net head estimations and, consequently, the determination of the optimal diameter of the penstock (Leon and Zhu 2014).

20.3.5 Efficiency of Hydroelectric Systems

The total efficiency (or simply efficiency) η of a hydroelectric plant for a given head and load is the ratio of the electric energy, which is provided to the electricity grid, to the hydraulic energy, i.e. the available net head. The value of η depends on scale (expressed in terms of discharge, since higher discharges ensure larger efficiencies) and the type of the turbine. Very large installations may reach efficiencies up to 95%, while small plants, with output power less than 5 MW, may have efficiencies between 80 and 85%, which again are quite high compared to other types of energy converters (see Sect. 20.1.2.2).

The total efficiency may be considered as the product of four individual components

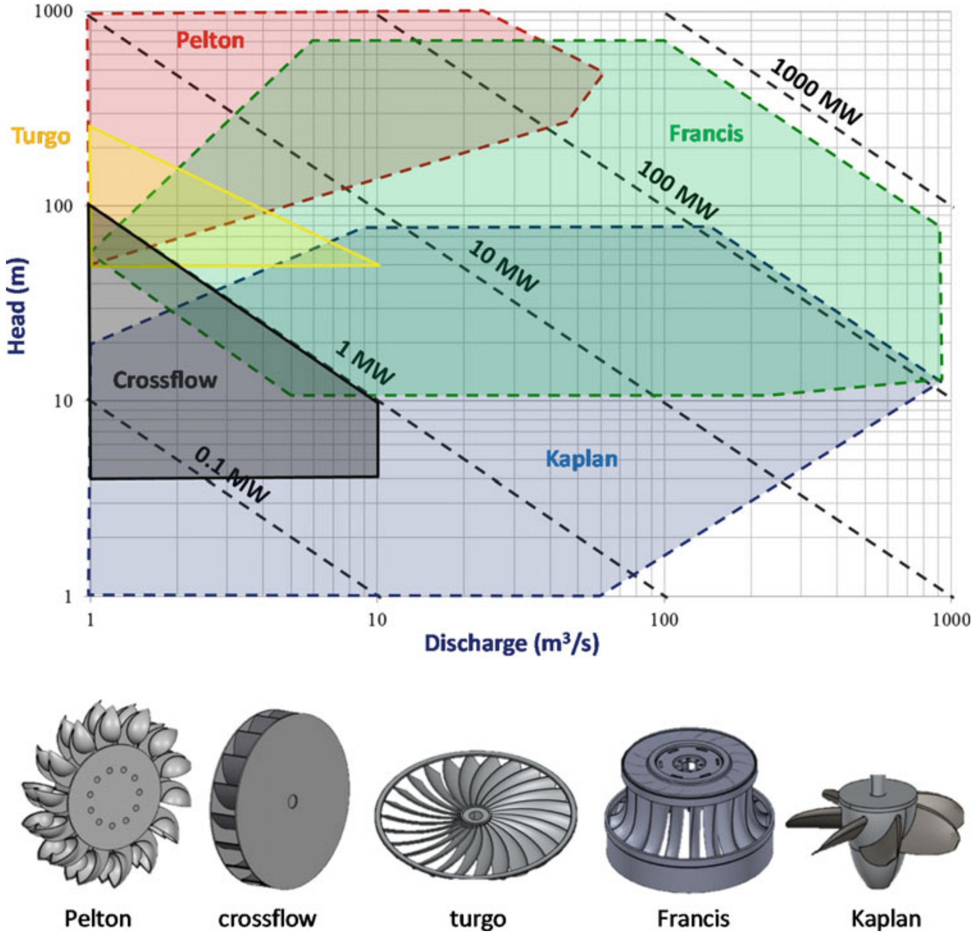
$$\eta = \eta_T \eta_G \eta_{TR} \eta_E \tag{20.14}$$

where η_T is the efficiency of the turbines; η_G is the efficiency of the generator; η_TR is the efficiency of the transformer, and η_E is the efficiency of the transmission lines. Typical values for the latter three are 0.96, 0.98 and 0.98, respectively.

The turbine efficiency is defined as the ratio of the mechanical energy provided by the turbine to the net head. The difference between the two energy quantities is due to:

- *Hydraulic losses*, which refer to friction losses of the fluid layers in motion, friction losses due to water crash on blades, local losses due to changes of tube section, etc.;
- *Volumetric losses*, which are only occuring in case of impulse turbines, and they are due to small amounts of water that are extracted to the atmosphere, without crashing on the blades;

Fig. 20.6 Recommended ranges of application of different turbine types



- *Mechanical losses* that are developed in the rotating parts of the turbine.

Therefore, η_T is also derived as the product of three components, i.e. hydraulic, volumetric, and mechanical efficiency, with typical values 0.90–0.96, 0.97–0.98 (only for impulse turbines) and 0.97–0.99, respectively.

Although in preliminary design and common management studies the efficiency is considered constant, it is actually a complex function of head and load. In real-world conditions, e.g. in case of large hydroelectric dams, the two aforementioned quantities are varying in time, since they depend on the reservoir level and the discharge, which are also evidently varying. As shown in Fig. 20.7, the variation of efficiency against head and discharge for different gate opening ratios is typically expressed by means of nomographs, which are experimentally derived and provided by the manufacturer of the turbine. For a specific turbine, there exists a theoretically optimal efficiency that is achieved for a specific combination of head and discharge. However, the actual optimum may differ, since the operation of the turbine is determined by the head-discharge relationship of the penstock, i.e. $H_n = H - h(Q)$ (where $h = h_f + h_L$), dictating the feasible operation range. Since across this range the efficiency may differ significantly, also taking quite low values, a key design objective is to ensure that the turbines will mostly operate as close to the optimal efficiency value as possible. In hydroelectric reservoirs, this is achieved by properly tuning the opening of turbine gates, thus adapting the outflow to the given head conditions.

20.3.6 Pumps and Pumping Systems

Pumps convert mechanical energy to hydraulic energy, thus allowing to lift water from a lower to a higher elevation or to increase the discharge capacity across a water-transportation system (or even to boost water conveyance from a higher to a lower elevation by adding energy for the increased frictional losses). Pumps are classified into two categories, namely *positive displacement* pumps, which deliver a fixed amount of water with each revolution of the rotor, and *rotodynamic* or *kinetic* pumps, which apply energy to the water by accelerating it through the action of a rotating impeller. Archimedes' screw pumps (see Sect. 20.1.1) are also another category, still in use, but it is not examined here.

Rotodynamic pumps are the most usual type used in water resource systems (Chin 2006). The pipe upstream and downstream of a pumping system are called *suction* and *delivery* pipes, respectively, conveying water from an upstream level z_1 (water source) to a downstream level z_2 (destination tank).

As shown in Fig. 20.8, the total energy head provided by the pump, called *manometric head*, is the sum of the following components

$$H_{\mathrm{m}} = z_2 - z_1 + h_{\mathrm{L}} + h_{\mathrm{f}} + V^2/2g \tag{20.15}$$

where h_{L} are local head losses at the pump; h_{f} are friction losses across the suction and delivery pipes, which are estimated by Eq. (20.9) as function of the diameter, roughness and discharge, and $V^2/2g$ is the kinetic energy at the downstream end, e.g. the destination tank (which is another local head loss). Equation (20.15) represents the hydraulic operation of the pipeline system, expressing the manometric head H_{m} as function of the discharge Q.

Each pump also has a *characteristic curve* or *performance curve*, showing the relationship between the manometric head H_m and the discharge Q. Thus, a combination of a specific pump with a specific pipeline has a unique operation point, which is determined by the intersection of the two curves (Fig. 20.9).

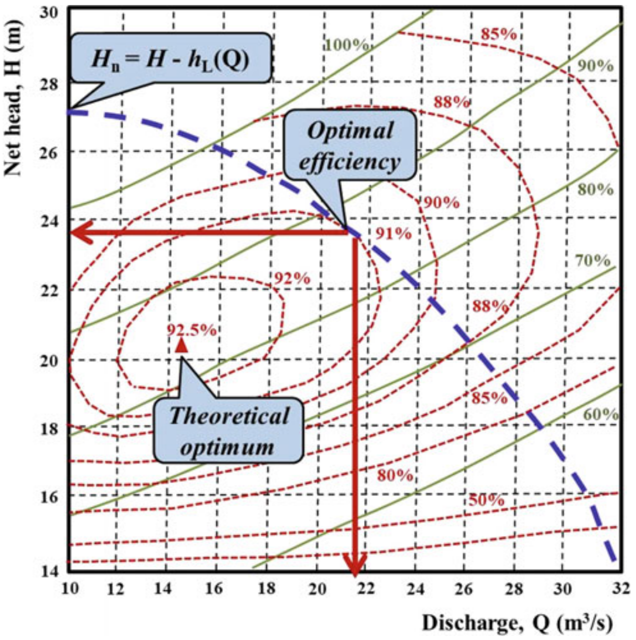


Fig. 20.7 Example of performance curves of a specific hypothetical combination of turbine and penstock, showing efficiency values for different head, discharge and gate opening ratios, along with a plot of the head-discharge relationship

Usually, a pumping station comprises a set of pumps that are put either in series (multistage pumps) or in parallel. In multistage pumps two or more impellers are arranged in series with the discharge from the first impeller entering the eye of the next one and so on. This layout is preferred when large heads are required, e.g. in a case of deep underground abstractions. In that case, considering N similar pumps, the total head is divided by N, while the total flow is conveyed through all individual pumps. On the other hand, in the parallel configuration, the discharge is divided by N, where the total manometric head is estimated by summing each of all individual pumps. We remark that whenever a pump in series or in parallel is added to the system, the operation point of the pumping system changes accordingly.

20.3.7 Reversible Turbines

Reversible turbines are specific types of hydrodynamic machines that can operate both as turbines and pumps. Such systems are typically installed in pumped-storage plants, which allow to pump water to an upstream location by consuming the available excess of electric energy (or low-price energy, e.g. during night), so to be retrieved later as hydropower. The importance of these systems has increased significantly due to the great expansion of renewable energy sources, such as solar and wind energy, which are highly-uncertain as the energy generation depends each time on current meteorological conditions (Koutsoyiannis et al. 2009). In this context, pumped-storage systems are essential to regulate the excesses and deficits of energy production through renewable sources, as discussed further in following sections.

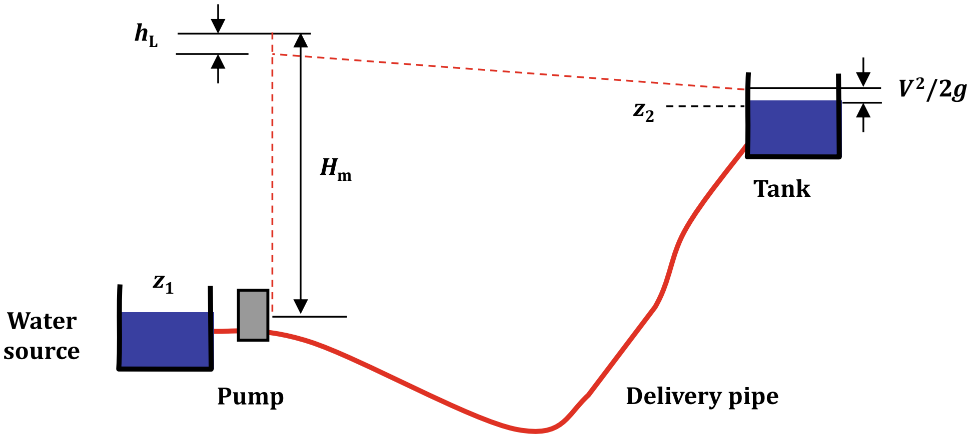
20.4 Design and Operation of Hydroelectric Systems

20.4.1 Classification of Hydroelectric Systems

Hydroelectric systems comprise a wide range of layouts, from large-scale reservoirs to minor run-of-river plants, which take advantage of the available dynamic and kinetic energy of water across rivers and streams. These may be classified into categories (a) to (g), according to a number of criteria that are listed below, which also dictate the design and management of such systems.

(a) Based on their *installed capacity*:
- Large hydro plants for $P > 15$ MW;
- Small hydro plants for $P < 15$ MW;
- Micro hydro plants for $P = 5$ to 100 kW;
- Pico hydro plants, for $P < 5$ kW.

Fig. 20.8 Sketch of a typical pumping system



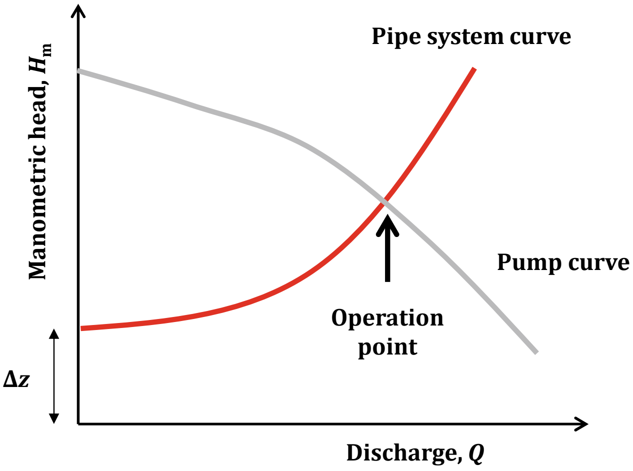


Fig. 20.9 Definition of operation point of a pumping system

The thresholds used may differ worldwide; for instance, the threshold for large and small plants typically ranges from 5 to 20 MW. Usually, but not exclusively, large plants are installed downstream of dams, to take advantage of the regulating capacity of the reservoir. Small plants may or may not have storage capacity, while micro and pico hydro plants only capture the kinetic energy of small streams to provide electricity to isolated homes or small communities.

(b) Based on their *head*:
- Large head for $H > 200$ m;
- Medium head for $H = 30$ to 200 m;
- Small head for $H < 30$ m.

As explained in previous section, the available head combined with discharge determines the selection of the turbine type.

(c) Based on the *location of the power station*:
- Power stations installed close to the dam;
- Power stations installed at a significant distance downstream of the dam;
- Power stations installed at an adjacent river basin (interbasin water transfer).

The typical case is the first, thus involving a penstock of relatively small length, in order to minimize the friction losses and the environmental impacts. Yet, there are cases where it is more advantageous to construct the power plant at a downstream location in order to increase the available head. Apparently, such a layout is economically efficient only when the river slope is large, so that the gains from elevation difference exceed the hydraulic losses due to the water being transferred at a long distance. An important issue to account for is the environmental impacts, since the water does not return to the river just downstream of the dam, as happens in typical configurations where the power station is located close to the foot of the dam.

Another case is the installation of the power station in a neighbouring basin, where the water is transferred through a pipeline connecting the two basins. This layout is preferred when there is a significant elevation difference between the upstream catchment, in which the water is gathered, to the one downstream, where the power station is installed. Typically, in large-scale interbasin systems, Pelton type turbines are used, as this option becomes economically efficient when the head is large enough. However, if the transfer is implemented for other reasons (e.g. if the principal objective is the transfer of water per se), then the head may be small.

(d) Based on the type of the *hydrodynamic machine*:
- Action turbines;
- Reaction turbines;
- Reversible turbines.

As already explained, action turbines are applied only in case of relatively small discharges and large heads, while reaction turbines are employed in any other case. Reversible turbines are applied within pumped storage systems, which require a cascade of two storage components, one upstream and one downstream. Although any combination of storage systems is generally valid, the most usual case is when a large hydroelectric reservoir (typically called head reservoir) is located upstream to implement long-term flow regulations, and a small-one downstream. Another widely used scheme comprises a reservoir, installed across the river, connected with a run-of-river tank, installed at a relatively small distance but at a higher elevation.

(e) Based on the *reservoir scale*:
- Large-scale reservoirs, having storage capacity larger than the mean annual inflow, thus ensuring multiannual regulation of the river flows;
- Medium-scale reservoirs, providing seasonal regulation of inflows;
- Small-scale reservoirs that are constructed to create an artificial head, but have minimal regulation capacity;
- Run-of-river plants without storage capacity.

(f) Based on the *time-schedule of turbine operation*:
- Continuous (or almost continuous) operation to provide base-load electricity;
- Intermittent operation to provide peak-load electricity;
- Pumped-storage operation to regulate energy production excesses and deficits from other sources.

It is well-known that a major advantage of (hydro) turbines is their almost immediate response, as they can be activated very quickly to adapt to changing energy demands. In this context, hydroelectric works are the most flexible source of electricity. In particular, large and medium-scale reservoirs may provide both base and peak load, since they offer enough storage capacity to operate independently of the inflows. However, in the current energy scene, comprising multiple energy sources, the typical operation of such works is for fulfilling peak energy demands by releasing water only during a few hours per day (a tactic called *hydropeaking*).

Small hydroelectric works with minimal or negligible storage capacity do not offer the opportunity to regulate outflows and they may also have intermittent operation. Actually, the energy production follows the variability of input process (in this case, streamflow), similarly to other renewables such as solar, wind and wave plants.

(g) Based on the *water uses* served by the reservoir:
- Single-purpose use, i.e. exclusively for hydropower generation;
- Multiple-purpose use.

Often, hydroelectric reservoirs serve additional water uses, such as water supply and irrigation, and also provide flood control. Environmental constraints are also imposed to the operation of existing and new dams, typically by means of releasing a constant (or sometimes varying) flow rate downstream of the dam to maintain riverine ecosystems. Such uses do not allow fully exploiting the hydrodynamic potential of the reservoir system, because water abstractions, water level regulations or water release schedules differ from the ones maximizing power production. In many hydroelectric reservoirs worldwide, recreation activities and associated touristic infrastructures have been developed as result of the generation of an artificial landscape and ecosystem of important aesthetic and environmental value, thus introducing additional constraints to the primary water use, which is energy production. Nevertheless, as multipurpose hydroelectric reservoirs are by definition subject to complex and generally contradictory objectives, a rational management policy is essential to ensure an optimal balancing of the associated conflicts (Christofides et al. 2005; Efstratiadis and Hadjibiros 2011).

20.4.2 Hydrological Analysis

For an assessment of an existing or planned hydroelectric system, it is essential to estimate the available water yield from the upstream catchment, as well as its variability, at multiple temporal scales. The surface runoff produced by the catchment is either directly available, by means of flow observations at the site of interest, or estimated indirectly, through a hydrological model. In the literature, numerous modelling approaches are available, of different levels of complexity.

The time scale of hydrological analysis depends on the scope of the study, but also depends on characteristic scales of the hydroelectric system. For the simulation of large reservoirs, a monthly time scale is typically adopted, while for small hydroelectric works the recommended temporal scale of hydrological analysis is daily. However, other aspects of the overall design and management may require another temporal resolution, for example, hourly or finer for flood analysis purposes, and daily for environmental flow assessment.

There are two ways of expressing the variation in river flow over the time period of interest, namely the hydrograph and the so-called *flow duration curve* (FDC), which is none other than the empirical exceedance probability plot (EEPP) of observed flows. The hydrograph (flow time series) depicts the evolution of flow for a specific time scale (annual, monthly, daily, hourly) over a specific time period. In case of hydroelectric works with non-negligible storage capacity, the sequence of flows plays a crucial role on the energy production, as it determines the required flow regulation by the reservoir.

The FDC (EEPP) is constructed by sorting the flow data in descending order and assigning an empirical exceedance probability based on the order of each value. Thus, the vertical axis represents the flow value and the horizontal axis the percentage of the time that the flow exceeds the given flow value. As the FDC (EEPP) expresses the distribution of flow values over a time period, a flatter curve corresponds to a more even spread of the annual inflow over the year. On the empirical probability distribution function, a proper theoretical model can be fitted using the typical probabilistic methodology. In this respect, the FDC (EEPP) of the river inflow at a specific site can be mathematically modelled as

$$P(Q) = 1 - F(Q) \tag{20.16}$$

where Q is the discharge; P is the exceedance probability of the value Q (also thought of as the fraction of time in which Q is exceeded), and F is the probability distribution function.

Figure 20.10a illustrates the hydrograph of 21 years of daily flow data. Based on it, one can recognize the seasonal variability of flows and the sequence of wet and dry periods. Figure 20.10b depicts the FDC (EEPP) constructed from the same data. As an example, from the FDC we easily see that the flow rate that is available for at least 30% of the time period is about 1.0 m^3/s; likewise, a flow rate exceeding 2.0 m^3/s is available in 15% of the time period.

20.4.3 Hydroelectric Reservoirs

Planning and management of hydroelectric reservoirs, often stated as an optimal control problem, remains a challenging issue, although a plethora of methods and software tools are available worldwide (e.g., Celeste and Billib 2009, Labadie 2004, Nicklow et al. 2009). At the start of the twenty-first century, the growing share of renewable sources with intermittent delivery created a need for novel means for energy regulation and storage. Classical system-based methods, i.e. linear, nonlinear, dynamic or stochastic dynamic programming as well as more advanced concepts and tools, such as fuzzy logic and neural networks, fail to provide the essential holistic approach with regard to the various complexities of the problem. Problems arise due to the large number of variables, the nonlinearities of system dynamics (e.g. the dependence of energy production on the reservoir level), the inherent uncertainty of future conditions (inflows, demands), as well as the multiple and often conflicting water uses and constraints that are involved in the operation of such systems.

Simulation allows for a detailed and faithful representation of reservoir systems and the evaluation of their performance, since it accounts for all technical (e.g., storage and flow capacities) and operational (e.g., desirable storage and flow ranges) constraints that are involved in the actual operation of such systems. In a following section we will see that the simulation can be performed within stochastics (Monte Carlo simulation) and can further be incorporated in an optimization framework, thus providing a powerful methodology for optimal design and management of complex hydrosystems.

Within a simulation context, the reservoir dynamics is described through the water balance equation, expressed in discrete-time form, i.e.

$$s_{t+1} = s_t + i_t - r_t - w_t \tag{20.17}$$

where s_t is the reservoir storage at time step t; i_t is the accumulated net inflow within time interval $[t, t + 1]$, i.e. runoff produced over the upstream catchment and precipitation falling over the reservoir surface minus water losses due to evaporation and possibly leakage (inflows may also include water diverted from adjacent catchments); r_t are the controlled water releases through the intakes, and w_t are (occasional) overflows through the spillway. For a given storage at the beginning of simulation s_0, a given sequence of inflows i_t (either projected or synthetically generated), and given a demand, Eq. (20.17) can be explicitly solved to provide the unknown quantities, i.e. storage, release and spill, at each time step. In particular, for a specific demand d_t, the actual release will be the minimum between the available water and the desirable release to meet this demand, i.e.

$$r_t = \min\,(s_t + i_t - s_{\min}, d_t) \tag{20.18}$$

where $s_{\min}$ is the reservoir storage at the minimum operation level, i.e. up to the intake (Fig. 20.3).

On the other hand, if the remaining storage after implementing releases exceeds the reservoir capacity $s_{\max}$, the surplus quantity is considered water loss due to spill, i.e.

$$w_t = \max\,(0, s_t + i_t - r_t - s_{\max}) \tag{20.19}$$

In the case of hydroelectric reservoirs, where a desirable energy production target is assigned, the demand at each time step is estimated on the basis of both the energy target, E, and the available head, $\overline{H}_{\mathrm{n}}$, by solving Eq. (20.4) for the volume, i.e.

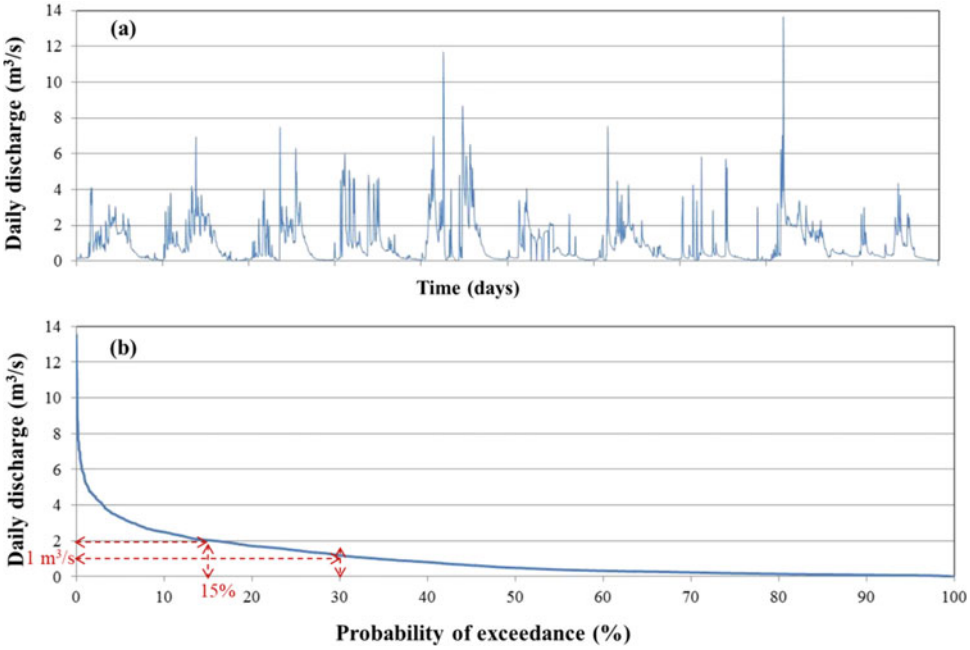


Fig. 20.10 **a** Daily hydrograph of a 21-year period, **b** Flow duration curve (empirical exceedence probability plot)

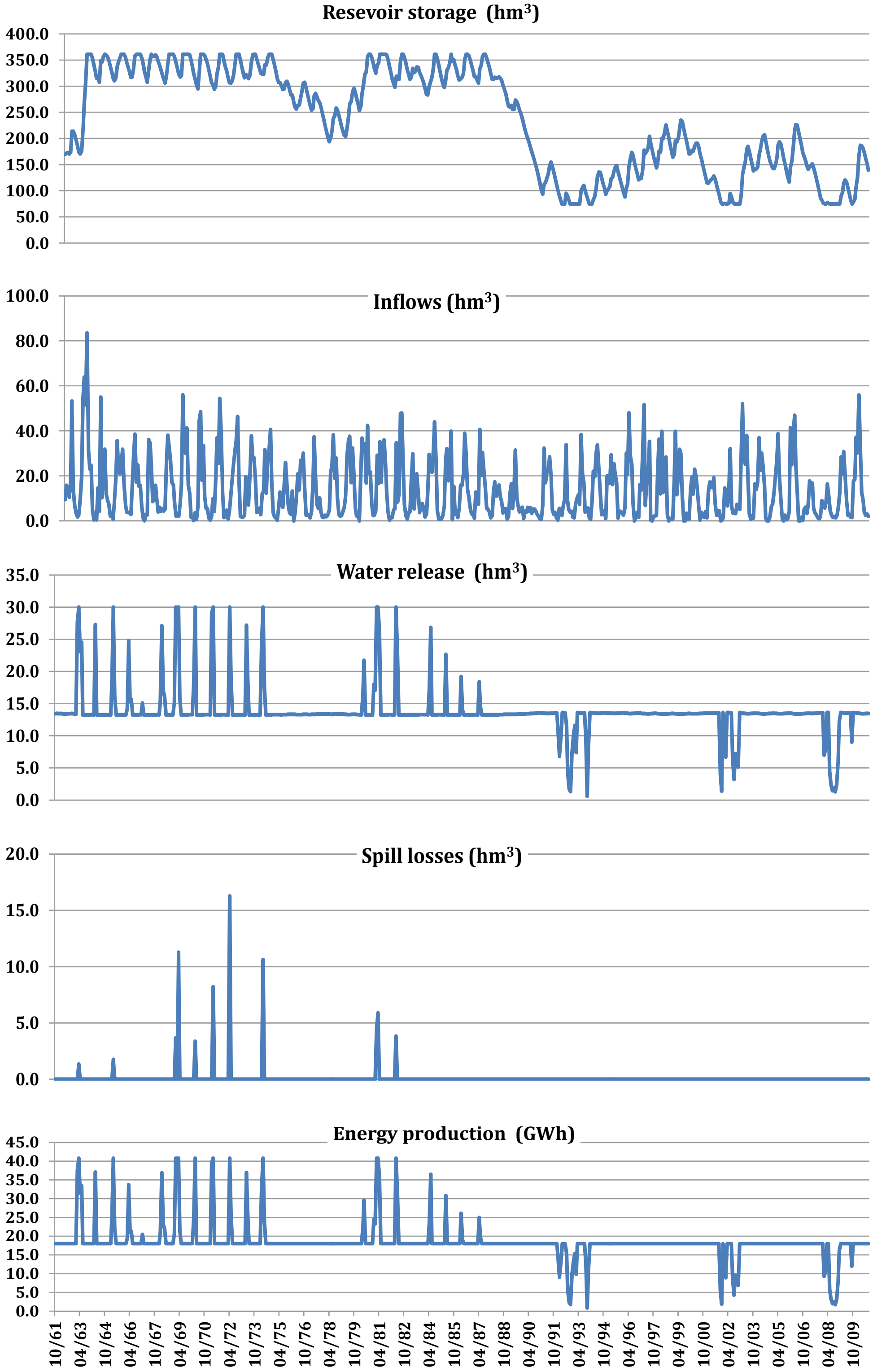
$$d_t = \frac{E}{\rho g \overline{H}_\mathrm{n} \overline{\eta}} \tag{20.20}$$

In Eq. (20.20), the average head $\overline{H}_\mathrm{n}$ is a function of the discharge and the reservoir level over the time interval. These are actually unknown. In order to provide an explicit solution in the simulation, the varying reservoir level is approximated as constant and equal to the level at the beginning of the time step. This approximation introduces some error in simulations, which requires adopting an appropriately small time interval in order to ensure relatively small fluctuations of the reservoir level within a time step.

Another key characteristic of hydroelectric reservoirs is the occasional generation of the so-called *secondary energy* by passing surplus flow through the turbines in order to avoid or minimize spill losses, thus releasing more water than the one imposed by the associated firm energy target. The price of secondary energy is lower than the firm one, as its production is unpredictable and not dictated by a systematic release policy. Actually, this resembles energy produced by other renewables, including small hydroelectric works, where the lack of storage capacity makes the energy production follow the pattern of randomly varying inflows instead that of the demand.

Figure 20.11 shows the output time series from a simulation example, involving the monthly operation of a hydroelectric reservoir at Central Greece, where a hypothetical constant energy target of 18 GWh per month is assigned. The total capacity of the reservoir is 361 hm^3 (cubic hectometres, that is, million cubic meters) and the net capacity is 286 hm^3. The last diagram in Fig. 20.11 depicts the time series of monthly energy production. The target of 18 GWh is fulfilled in 554 out of 558 of simulated steps, thus the firm (reliable) energy is ensured with reliability up to 554/558 = 94% on a monthly basis. Moreover, in 50 out of 558 steps, the energy production exceeds the target, thus this surplus is considered secondary energy. In this example, there seems to be a clustering of wet years, resulting in water losses due to spill and generation of secondary energy, and another clustering of dry years, resulting in energy deficits. This phenomenon is known as *long-term persistence* and is associated with the changing hydroclimatic behaviour, the so-called Hurst-Kolmogorov dynamics. As explained in Sect. 20.8.3, this natural behaviour influences greatly the design and management of water-energy systems (Koutsoyiannis 2011b).

The simulation procedure can be generalized to include additional reservoirs as well as other hydrosystem components. Moreover, it can be easily combined with a stochastic model to generate synthetic inflows for long simulation horizons, which should essentially reproduce the long-term persistence, and an optimization model to derive a release policy that ensures the optimal performance of the system. Optimization is substantially facilitated if the entire representation is parsimonious, i.e. if the number of control variables is kept as small as possible. This is ensured through a suitable system parameterization, in terms of parametric expressions of operation rules for the major system controls (e.g. reservoirs, power plants). The above scheme is also referred to as *parameterization-simulation–optimization* framework, which is a generalized Monte Carlo methodology for modelling hydrosystems of any complexity (Koutsoyiannis and Economou 2003; Koutsoyiannis et al. 2002). This approach also allows for evaluating the system operation, constraints and objectives in probabilistic terms and also expressing firm (or better named *reliable*) energy in terms of *reliability*.


Resevoir storage (hm^3)

Inflows (hm^3)

Water release (hm^3)

Spill losses (hm^3)

Energy production (GWh)

Fig. 20.11 Example of monthly simulation of Plastiras reservoir, Central Greece, considering the observed inflows of years 1961–2010, and by assigning a constant energy demand of 18 GWh per month (adapted from Efstratiadis and Hadjibiros 2011)

20.4.4 Small Hydroelectric Works

As already mentioned, a hydroelectric plant is typically classified as small or large by considering a threshold on its installed capacity. This threshold varies considerably around the world, but values between 5 to 20 MW are the most common. Generally, most of such systems have negligible storage capacity, thus their design aims at maximizing the power production by capturing as much of the available runoff as possible.

Figure 20.12 illustrates a sketch of the most characteristic type of a small hydroelectric work, referred to as run-of-river plant. The main elements of the system are: (a) a weir with a water intake that controls the amount of river flow to be used for hydroelectricity, (b) a channel that conveys the water to forebay tank, (c) the penstock, (d) the power station, and (e) a tailrace that conveys the water back to the river. In the typical layout of Fig. 20.12, the power station is located far away from the intake to ensure an economically effective elevation difference between the forebay tank and the power station, but the case that it is embodied in the intake is also common.

For a given installed power capacity P and hydraulic head H, the turbines produce energy for a certain range of discharges and associated efficiency values. Except for very large flow values, the relationship between the discharge and the efficiency is monotonically increasing. The discharge ensuring the maximum power production is referred to as *nominal discharge*. For smaller discharge values, the turbine operates at lower power, while below a threshold equal to 10–20% of the nominal discharge, the turbines do not produce electric energy. In this respect, the turbines operate within a specific flow range [$Q_{\min}$, $Q_{\max}$].

The nominal discharge is a key element of the overall system design, since it also dictates the capacity of the water intake, the channel, and the forebay tank. Typically, the latter has very limited regulation capacity, because its objective is preserving a practically constant upstream head. Under this premise, the water intake is designed to capture up to the nominal discharge of the turbines $Q_{\max}$, while the surplus amount overflows from the weir to the river. During periods that the river flow is lower than $Q_{\min}$, the power station stops its operation. At all intermediate flow ranges, all available water is used for energy production, which depends on the actual discharge and associated efficiency of the system. The key difference of the above configuration with a typical large hydroelectric work is the lack of the regulation capacity offered by the reservoir. The lack of water storage makes impossible to exploit flows that are out of the operational range [$Q_{\min}$, $Q_{\max}$]. In contrast, a hydroelectric reservoir not only can take advantage of any flow, but also ensures a scheduled energy production under optimal flow and efficiency conditions. For as the storage capacity increases, the reliability of the energy production also increases, since it absorbs the fluctuations of inflows at the seasonal and the over year scales. The higher the variability of inflows, the larger the reservoir capacity should be to minimize losses due to spills or deficits due to long-term droughts.

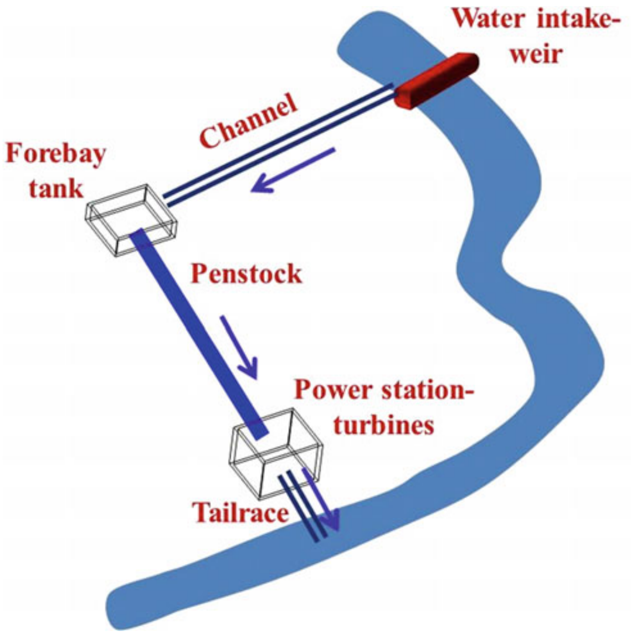


Fig. 20.12 Main components of a small hydroelectric work

Due to the lack of a storage component, run-of-river hydroelectric plants can exploit only part of the potential hydrodynamic energy. In this respect, key objective of their design is to maximize the long-term energy production via a proper selection of a turbine mix that ensures a large enough flow range [$Q_{\min}$, $Q_{\max}$] and as high as possible efficiency rates. Usually, this problem is examined by considering the flow-duration curve at the site of interest, which allows defining on a mean annual basis (a) the percentage of the exploited water volume by aggregating the flow-time curve within the range of operational discharges and (b) the corresponding time of turbines operation. A numerical example is given in Sect. 20.10 at the end of the chapter.

20.5 Energy-Mix and Hybrid Water-Energy Systems

20.5.1 Energy Systems Design

In order to satisfy energy demand on a national scale, each country uses a combination of various energy sources, which is typically referred to as “energy mix”. Although some types of fuels are strongly preferred for some needs, for example, petroleum for transportation, in the case of electricity production, there is a high degree of flexibility in configuring the existing energy mix. Isolated areas, such as remote islands not connected to the national grid, may have their autonomous mix. Remote stand-alone power systems that implement renewable energy technologies, by mixing two or more renewable energy sources, have been known as hybrid renewable energy systems. Hydropower is the most important component of such systems, as it provides increased system efficiency as well as greater balance in energy supply.

The main factors that influence the energy mix of a country are the following:

- The quantity and type of energy demand to be satisfied.
- The available energy resources (and their potential), such as availability of fossil fuels, existence of hydropower, wind and solar radiation potential and geothermal fields.
- Political conditions in the wider area that are related to fuel and energy transfer.
- Construction, maintenance and operation costs, i.e. life-cycle cost of energy works.
- Social acceptance of environmental issues associated with, for example, nuclear energy use, CO_2 production, or the influence of energy production on fauna and flora.

In general, electrical grids suffer from the critical limitation that they must be continuously fed with the same amount of energy that is consumed. As the electric energy demand is, practically, uncontrollable, the electric energy production must be continuously adapted to follow the demand that changes irregularly. The long-term statistical characteristics of energy consumption time series in an electrical grid, e.g. year-long, determine the design of the grid and the composition of the energy mix. The most important statistics are the maximum and minimum electric energy demand at fine time scales, e.g. hourly or less.

The minimum electric energy demand (base load) determines the threshold of energy that must be continuously produced while, the maximum demand (peak load) determines the minimum installed power capacity of the electrical system.

The ability of a power plant to contribute to synchronization of production and demand in an electrical grid that uses various energy resources depends on three important issues:

- *Control and predictability of energy production.* In thermal power plants the energy production is under the control of the operators, but it is not easily adaptable to changes; it depends only on fuel availability and operational readiness. However, for renewable energy resources the amount of control of the operators over the process depends strongly on the type of resource. For some resources energy production is completely controlled (e.g., biomass, geothermal), for others there are limits on control, but those limits can be reliably predicted (e.g., tide). Finally, there are resources that depend on unpredictable natural processes (e.g., wind speed, solar radiation, water flow, waves). In these cases, the energy production has poor predictability and cannot offer reliability to electric energy grids. This is a great weakness, making them more difficult to fit into an energy mix than more conventional sources. To promote them, states have prioritized the modification of their energy grids to allow absorption of the electricity produced from this type of renewables. Controllability and predictability of hydropower tend to be high when water is stored in large hydroelectric reservoirs; in that case the system is vulnerable only during long-term droughts.
- *Time that is required to adjust the energy production.* The time that is needed to change the energy production to follow demand depends on the type of power plant. This time ranges from several hours (or even days) for coal and nuclear stations to a few hours for natural gas thermal stations, and to a few minutes for hydroelectric stations. The adaptation time of power plants determines their role in electrical systems. Peak loads are covered mainly by hydroelectric stations and base load mainly by coal and nuclear stations.
- *Ability to store energy.* The issue of electric energy storage is very important, especially in cases that renewable energy sources represent a considerable share in the energy mix. In fossil and nuclear fuels, the energy is stored inside the material, and the total amount is measurable and expressed by local and global reserves. The installed capacity of thermal power plants is designed based on the desired degree of exploitation of the available (local or regional) reserves. Considering the renewable resources, opportunity of storage is only offered by hydropower (using reservoirs) and biomass. Additionally, for geothermal fields, the total “stored” energy can be estimated, while tidal energy is reliably predicted. Surplus energy by other renewable sources could be stored through pumped-storage schemes or in batteries. From the start of the twenty-first century extensive research and development on batteries is in progress, but at that point in time batteries were considered an option suitable only for smaller scale systems.

20.5.2 The Concept of Capacity Factor

The ability of electric energy production by a power plant that has a specific installed power is expressed by the capacity factor (CF). CF over a time period is defined as the fraction of the actual electric energy produced from a power plant to the electric energy that could be produced considering continuous operation of the plant at the maximum installed power. For a specific power plant, the potential electric energy that can be produced is a structural characteristic, calculated by multiplying the installed power by the time period length. Thus, the CF always depends on the quantity of electric energy that is actually produced by the plant.

The CF expresses different characteristics in various electric power plants. In thermal power plants, the installed power is determined taking into account economical and operational parameters, such as the energy demand, the availability of fuels, as well as socioeconomic and operational parameters. Energy production is controlled, except in emergency situations such as accidents, lack of fuels, etc. The CF of a time period can be scheduled taking into account the desired operation time and the active power used. Theoretically, a thermal power plant for a given time period may have a unit CF, if it is operated continuously at maximum power.

In wind and solar power plants, the energy production is uncontrollable as it depends on a meteorological process (wind speed, solar radiation). The installed power of a specific plant is exploited only for time periods that the associated input takes on values within a specific range. Otherwise, the power plant produces less energy or remains inactive. For example, contemporary wind turbines produce the energy that corresponds to the installed (nominal) power, when wind velocities are between 12 and 25 m/s. For lower velocities (typically, 3–12 m/s) turbines produce only a fraction of its maximum output. For wind velocities outside the range of 3–25 m/s turbines cease to operate. As a result, it is impossible for a wind turbine to have annual CF approaching 1, and values of about 0.3–0.4 are common. In solar power plants, the CF is limited by the sunshine hours. As the potential sunshine hours are, on average, half of the total, there is a physical limit of 0.5 to CF in solar power plants. Yet, less or even no energy is produced when sun is located low on the horizon or the weather is cloudy. For these reasons annual CFs of about 0.2–0.3 are common in solar power plants.

20.5.3 Combined Management of Water Energy Systems

Water and energy are vital goods for human societies and must be provided in a sustainable, reliable, cost-effective and environmentally friendly way. Therefore, the design, operation and management of water-energy systems are very important issues.

Water and renewable energy sources are sustainable by nature (Koutsoyiannis and Efstratiadis 2012). The unexhausted solar energy drives the eternal hydrological cycle that feeds the natural system with water. Solar energy also drives the processes of wind, sunshine, waves, and vegetation, supporting the water-food-energy production. Additionally, the astronomical motion controls tidal energy. However, the concept of water-energy sustainability in societies is related to ensuring satisfaction of the various demands, not only in the present but also in the future. Water and renewable energy sources must be synchronized with various demands in space and time, and therefore, storage and conveying works are necessary. Water and energy storage are essential to water-energy systems.

Key concepts of uncertainty, reliability and optimality should be taken into account in order to ensure rational and sustainable solutions to the design and management of highly complex water-energy systems. As discussed herein, uncertainty is an inherent property of hydro-meteorological processes that are related to water and renewable energy sources. As predictions of future water and energy production using deterministic methods are impossible, the statistical behaviour of the associated natural processes is studied, and stochastic modelling is performed for uncertainty quantification. The uncertainty of water-energy resources availability strongly affects the reliability of water-energy systems. The latter is typically expressed either as a constraint, imposed by the system manager, or as an objective to maximize, which is equivalent to minimizing the risk of water-energy shortage. Nevertheless, optimal design and management of water-energy systems should ensure both minimization of construction and operational costs and maximization of their long-term performance in terms of safe yield, mean economic benefit, firm energy, etc. In water-energy system optimization, there are several hard issues to handle such as the large number of variables and constraints, nonlinearity of system dynamics, uncertainty of future supplies and demands, and competitive or conflicting objectives.

20.5.4 Suitability of Hydroelectric Reservoirs for Integrated Water-Energy Management

Several characteristics make hydroelectric reservoirs essential for water-energy systems:

- In contrast to other renewable sources, hydropower produced by large reservoirs is almost fully controllable. While streamflow is a stochastic process, when stored in the reservoir, its variability is regulated which allows for scheduled energy production in the long run. As the storage capacity of a reservoir increases, the reliability of energy production also increases. This is because the ability to store water smooths out the natural fluctuation of inflows during drought and flood periods and ensures that electric energy is produced according to schedule.
- They can serve more than one purpose. The release of water for energy production can be combined with local water uses (irrigation, domestic), flood protection and recreational activities in the reservoir area.
- Hydroelectric reservoirs store the electric energy production of other energy sources (mostly renewables) using mainly pumped storage systems. These systems pump water to a higher location, when there is excess of energy in the grid (e.g. during night hours or even during sunshine hours in the case that the solar energy is a substantial component of the energy mix), and later, when lack of energy occurs, retrieve the water to generate hydropower. The efficiency of pumped storage systems is very high (more than 80% for large-scale systems). Today several wind farms store the produced electric energy in nearby pumped storage projects.
- Hydropower is a flexible source for electricity management, since the produced energy can be increased or decreased very quickly to follow changing energy consumption in the grid. The start-up of hydro-turbines is in the order of few minutes, much shorter than for other types of power plants.
- Hydropower offers sustainability as it ensures enough energy to satisfy various demands now and in the future. As fossil fuels are limited in quantity and expendable, while most renewable energy sources are unpredictable and uncontrollable, hydropower can support sustainability in the electric grids.
- While the installation cost of hydroelectric reservoirs is relatively high, hydroelectric stations have long economic lives (50–100 years) and low operational and maintenance costs.

The main disadvantages of hydroelectric power plants are related to their environmental impacts. The main ones that are referred to the literature are: (a) inundation of large areas of land and possible displacement of local population, (b) changes to water and sediment regime of the river, (c) block of fish migration, and (d) failure risks for downstream settlements and infrastructures. These issues are analysed in more detail in Sect. 20.7.1.

20.5.5 An Illustrative Example of Renewable Resources Management

On islands that are not connected to the electric grid, the electric energy is mainly produced by oil-fuelled power plants, whose unit cost is high due to oil import cost. Therefore, the integration of renewable resources in the energy mix is essential for reducing the financial and environmental cost. A pilot investigation of how various energy resources (renewable and fossil fuels) can be evaluated using technical, environmental and economic criteria in order to create the appropriate electric energy mix for a non-connected island can be seen in Chalakatevaki et al. (2017). Particularly, six basic renewable resources are examined (solar, wind, marine, hydropower, biomass and geothermal) for the energy mix in a non-connected island at the Aegean Sea (Astypalea, Greece). Table 20.2 summarizes the outcomes from two case scenarios, based on a preliminary (but indicative) analysis where each source has to be harvested according to the energy demand (Mavroyeoryos et al. 2017) and economic analysis (Karakatsanis et al. 2017) for the selected case. Therefore, a separate stochastic and cost analysis was first employed for solar energy (Koudouris et al. 2017), wind and marine energy (Moschos et al. 2017), hydropower with a pumped storage system (Papoulakos et al. 2017), biomass and geothermal energy (Chalakatevaki et al. 2017). The second case that was finally selected includes two wind turbines of 75 m height, 3800 m^2 of photovoltaic panels, two wave converter installations, addition of a small hydro turbine to the existing dam, a biomass facility fed with 180 t/year of cultivated biomass, and a pumped storage system that includes a reservoir with storage capacity of 0.5 hm^3, a 2 km penstock and a hydro turbine installation. The total installed power of the proposed solution is 4.8 MW (with a peak demand of 2.6 MW) with a total cost of more than 10 M€.

20.6 Marine Energy

Marine energy can be considered as the most widely spread, reliable and efficient nearshore renewable energy resource with a theoretical annual potential of approximately 400 EJ or 10^5 TWh. However, while the technology for harnessing other renewable resources, such as wind and solar, is continuously evolving, marine energy is expected to make a

Table 20.2 Analysis of two selected scenarios for a small non-connected island

Source	Estimated cost (M€/MW)	Power (MW)	
		Case 1	Case 2
Wind turbine	1.5–2	1	1
Solar panels	2–3	0.5	0.5
Hydroelectric dam	1	0.08	0.08
Wave energy converters	3–4	0.3	0.6
Geothermal power station	1–2	0.5	–
Pumped storage system	1.5–2	–	1
Biomass power station	2–3	2.1	1.6
Total		4.5	4.8

Source Chalakatevaki et al. (2019)

significant contribution in the twenty-first century due to its nascent stage of development (Edenhofer et al. 2011). A promising technology is the exploitation of waves and tides for which there are some wide-scale industrial applications (de Falcao 2010) and has the largest expected future cost reduction among all renewable resources (Magagna and Uihlein 2015).

The ocean energy sources can be divided into two main groups (see Table 20.3): the ones generated by gravitational forces (waves, tides, currents) and those that harvest the oceans chemical or heat potential (temperature and salinity differences).

Specifically, there are three main ocean energy resources mostly related to the fluid properties of the ocean water. The first is the energy present in the waves generated by the wind passing over the surface of the ocean. The largest wave heights occur at high latitudes (greater than 40° from the equator), where the trade winds blow across large stretches of open ocean and transfer power to the sea swells (OES-IEA 2012). Waves are considered as a promising resource with a rising technology on energy control (de Falcao 2010, Falcão and Henriques 2016, Roberts et al. 2016 and references therein), however still facing considerable barriers due to the high cost for energy absorption, relatively to the other renewable resources (Uihlein 2016, and references therein). Additionally, the environmental impacts on the coastline can be significant, and great caution is required for the estimation of the optimum location and orientation of the devices. Nevertheless, wave energy is highly sustainable with a significant absorption density of 2–3 kW/m^2 compared to solar 0.1–0.2 kW/m^2 and wind 0.4–0.6 kW/m^2 densities (López et al. 2013). Also, the operating time of the wave energy projects is even up to 90%, a very high value compared to the 20–30% of the solar and wind energy (Pelc and Fujita 2002)

The second is tidal energy (range and currents), which is one of the most reliable renewable resources due to its high predictability, when compared to solar and wind resources as well as the other ocean resources. Since tides depend almost exclusively on the relative position of the Earth, the Sun, and the Moon (the rest of planets have minor effects), the tidal period and amplitude in oceans can be predicted very accurately for many years, assuming that there are no significant changes (e.g. anthropogenic and geological) in the coastlines. Tides have several periodic cycles (Schureman 1963) with the most important one for energy production being the diurnal (and semi-diurnal). The height difference between successive high and low tides varies from 0.6 m in mid-ocean to more than 15 m at a few continental locations (Sleiti 2017; Twidell and Weir 2015). Tidal power can be efficiently harvested only in relatively shallow waters and coastal regions, and so technical potential is likely to be significantly less than theoretical potential (Edenhofer et al. 2011).

A third energy source, closely related to the above, originates from the ocean currents which are generated

Table 20.3 Ocean energy sources along with an indicative potential energy production in a global or local scale

Source	Indicative potential energy production
Wave energy (wind-driven)	30 000 TWh/year (theoretical potential)
Tidal range (rise and fall)	10 000 to 30 000 TWh/year (theoretical potential)
Tidal currents (in coastal regions)	e.g. 100 TWh/year (Europe and China)
Ocean currents (wind-driven and thermohaline ocean circulation)	e.g. 0.2 TWh/year (Florida Current, Gulf Stream, North America)
Ocean thermal energy conversion (OTEC)	45 000 TWh/year (theoretical potential)
Salinity gradients (osmotic power)	1 500 TWh/year (theoretical potential)

Source Edenhofer et al. (2011)

mostly by the Coriolis effect as well as temperature and salinity differences (Edenhofer et al. 2011). Similar to the above two sources, the kinetic energy of these currents can be efficiently harnessed nearshore, particularly where there are constrictions, such as straits, islands and passes (OES-IEA 2012).

Two other main ocean energy resources mostly relate to differences in the physicochemical properties of the ocean waters and, in particular, temperature and salinity differences. One is the osmotic pressure created by the salinity differences between fresh and sea water at river mouths, but it has a low potential energy status due to its limited exploitation (Edenhofer et al. 2011); the other is the ocean thermal energy. The latter is regarded as a candidate marine energy resource (Nihous 2007) since the temperature in deep ocean water tends to be relatively constant (around 4 °C), and thus, the heat exchange between warmer surface waters can be quite significant for a wide range of locations and for a large portion of the year (OES-IEA 2012).

20.7 Environmental Impacts

The population boost and the steep increase of energy demand per capita during the twentieth and twenty-first centuries have dramatically increased the water and energy needs. In this respect, water-energy infrastructures have expanded massively and impacted vast areas in previously undeveloped lands, causing major changes to the landscape at a global scale. Indicatively, there are approximately 58 000 large dams in the world today (this is a total number of dams, including those used for irrigation, water supply, etc.) (Tanchev 2014), and several countries have exploited more than 80% of their economically feasible hydro potential (Leckscheidt and Tjaroko 2003).

Criticism on dams over their environmental impacts has been harsh, and legislation in many countries considers the energy produced from hydroelectric dams to be non-renewable (Koutsoyiannis et al. 2009) due to their impacts on the riverine systems. However, these environmental impacts can be managed, to an extent, through optimized siting with the use of environmental impact assessment regulation as well as through the utilization of various technologies that have been developed for their mitigation, such as fish passes (DVWK 2002), sediment management techniques (Annandale et al. 2016), etc. Thus, the irreversibility of environmental impacts of dams has been questioned, and their importance for water storage and renewable energy generation is considered to justify their further expansion with adequate environmental planning (Klemeš 2007; Koutsoyiannis 2011a).

Below we compile the major and commonly cited environmental impacts of hydroelectric power plants combined with brief references on methods that can be utilized to reduce or avert them, when such methods exist. Not all of the examples and cases presented refer to dams used solely for hydroelectricity, since most impacts are common to all dams. Moreover, a brief reference to other environmental problems related to the use of water for energy, for example, use of water for cooling in thermoelectric plants, is also made.

20.7.1 Hydroelectricity

20.7.1.1 Water

Among the impacts of hydroelectric dams to the environment, the most evident is on river dynamics. A dam changes the spatio-temporal route of water transforming a riverine system into an artificial lake. In particular, a dam blocks the flow of water from upstream collecting it in the reservoir and transfers the temporal and quantitative control of the hydraulic supply from nature to man.

The transition of the hydrological system from riverine to lacustrine (referring to lake) causes changes to both the physical and chemical characteristics of water. Initially, in relation to the temperature of the water, it is observed that the water, becoming almost stagnant, ceases to present the significant variation in temperature that is usual for the water of a river throughout a year. It ends up fluctuating with significantly reduced variation around a higher average temperature (Maheu et al. 2016), and very often, in reservoirs, stable temperature zones appear with temperature decreasing with increasing depth. In some cases, the lower layers of water develop temperatures much lower than those of natural rivers, and when water from these layers is released, it may affect downstream ecosystems. Releasing water from the surface layers is an easy solution to this problem provided suitable outlet pipes have been designed.

The chemical characteristics of water are also prone to alterations as a result of the impoundment, especially when trees and flora are not removed from the reservoir area prior to the inundation. The density of pre-existing vegetation is also a significant determinant of the emergence of such phenomena. If large amounts of organic matter were present in the reservoir area, the dissolved oxygen concentration in the water can be noticeably reduced even for more than twenty years after the inundation of the reservoir (McCartney et al. 2000).

Finally, there are effects on the type and amount of aquatic biota present in the reservoir, where one can find plankton, aquatic plants, seaweeds that surround submerged objects and floating plants, which grow mainly in tropical zones.

20.7.1.2 Geology–Geomorphology

Hydroelectric plants are complex engineering projects consisting of many separate elements and supporting engineering works like road works for access to the dam area, excavations for slope stability in the abutments of the dam and various other types of earthworks. These alter the geomorphology of the dam area, and the geological impact of the dam is also extended to distant downstream areas due to the significant amounts of sediment trapped. Less often, hydroelectric dams are associated with several geological effects such as landslides in the reservoir area, erosion of the river bank downstream of the dam, as water released through the dam is clear of sediments (Collier et al. 1998), or triggering of earthquakes (Dixon et al. 1989)

Nevertheless, as far as the geological impacts of the dam are concerned, the main and most cited effects are related to the trapping of sediment. Dams retain a large proportion of the materials that rivers would normally carry away downstream, especially, when there are no plans for removing deposits. Notably, based on Hay (1994), the sediment flow of Turkey's Black Sea rivers has decreased from 70 × 10^6 t/year to 28 × 10^6 t/year due to the operation of hydroelectric dams. According to the study of Walling and Fang (2003), the sediment loads of 145 more rivers have been significantly reduced after the construction of dams, as reported by UNESCO Office in Beijing, IRTCES (2011)

All these phenomena depend on many different factors varying from random events, like earthquakes or landslides, to the quality of the design of the plant (e.g., the design of the dam can include measures to reduce sediment trapping) and do not appear in every dam. In terms of sediment trapping, many different reservoir sedimentation measures have been developed, taken both in the reservoir area and at the dam site. For example, these include dredging with mechanical equipment, flushing from the bottom outlets of the dam or sluicing when floods with heavy sediment load are expected (Schleiss and Oehy 2002). Even though relevant research continues, new methods are developed and the older ones are improved, with early twenty-first century state of the art, sediment trapping cannot be completely avoided (Morris and Fan 1998).

20.7.1.3 Atmosphere and Microclimate

The effects of the dam on the microclimate of the reservoir area can be divided into short-term and long-term. Short-term effects are related to the construction of the dam and its appurtenant structures, a process that usually lasts several years, and they include vibrations, dust and noise pollution. Long-term effects include an increase in the humidity in the periphery of the reservoir due to the evaporation of water and the intensification of storms, as reported in Mediterranean and arid areas (Degu et al. 2011).

Regarding the impact of hydroelectric dams to the atmosphere, the main phenomenon observed is increased gas emissions. The phenomenon is intensified when the area of the reservoir has not been cleaned from biomass prior to the inundation and is apparent mainly in tropical areas (Fearnside and Pueyo 2012) due to more abundant vegetation. The main gas produced in these cases is methane, which is a result of the decomposition of the biomass inside reservoir. The exact type of biomass that triggers the phenomenon is soft biomass, from leaves and branches (McCartney et al. 2000).

20.7.1.4 Fauna

The effects of dams on ecosystems are many and complex. They concern the fauna and flora of the reservoir area, as well as the people living there and people who use the power produced by the hydroelectric power plant. In relation to the fauna of the area of the dam, both negative and positive effects from dams have been observed (Bardach and Dussart 1973). In literature, negative impacts have been studied more thoroughly. These include, for example, the inundation of animal habitats by the reservoir with various examples from different countries, in some cases even habitats of endangered species have been affected. Moreover, the effects of the dam on aquatic fauna are also significant, as the continuity of the river is interrupted, therefore its flow changes and the type of ecosystem changes from riverine to lentic. All of the above are causes of problems for fish populations with impacts being more significant on migratory species (e.g. salmon, sturgeon etc.), which can end up being threatened with extinction, especially when fish ladders for free movement of fish from upstream to downstream and vice versa are not built.

However, cases of reservoirs that helped enrich and improve the life of their ecosystems have also been reported. In the study of Bergkamp et al. (2000), 66 dams were examined, regarding their impact on the biodiversity of fish in the ecosystem, and 27% of the dams showed increase in biodiversity and 73% decline. Similar conclusions about artificial lakes that have been evolved to wetlands of high biodiversity were drawn for hydroelectric reservoirs in Greece (Tzitzi 2008).

Nevertheless, hydroelectric projects are certainly major interventions on the environment that may even affect the fauna of areas relatively far from their location. A typical example is the case of the Aswan Dam in Egypt, where the containment of sediment from the dam caused a significant reduction in the sardine population in the delta of Nile region (Biswas and Tortajada 2012), which is approximately 850 km away from the dam. This population was an important factor in the income of the fishers of the area, and the decrease observed in the volume of fish caught in the first years of operation of the dam was spectacular: from 18 000 to 400–600 t within five years. Remarkably, the population returned to fairly high levels after approximately 20 years (El-Sayed and Dijken 1995).

20.7.1.5 Flora

The most significant impact on flora by a dam and its reservoir is the loss of forest areas and natural vegetation in general. These areas include the site of the reservoir itself, where the vegetation is either flooded or removed, but also all other areas that are affected from the construction of the dam's appurtenant structures. It is worth noting that efforts have been made to preserve some of this vegetation, especially, in cases where rare or endangered plants grow in the reservoir area. Such an example is the Three Gorges dam, China, where more than 200 plant species, including 37 endangered species, were transplanted to other locations (Zhang and Lou 2011).

During the dam operation, the development of lakeside vegetation that normally grows in natural lakes is usually restricted by variations of the reservoir level. This is due to the fact that this type of vegetation is particularly sensitive to small changes in the ecosystem, let alone the intense variation in the level of an artificial lake. Thus, it is common that instead of lakeside vegetation, the creation of a dead-zone around the shore of the reservoirs is observed (Christofides et al. 2005).

The effects of reservoirs on the flora also extend to areas downstream of the dam as a result of the alteration of the physical variation of the water flow. The outflows through the dam are controlled by various structures, in terms of volume and timing of the flow released, and also typically have different physicochemical characteristics from the water of the natural river system. Consequently, when the water characteristics (chemical, physical, hydrological, etc.) are greatly modified, there is a risk for species that live downstream of the dam and are dependent on them (Kingsford 2000). As far as the variability of flow is concerned, there have been numerous studies proposing methods for maintaining an ecological flow similar to the natural, which may also require adapting the operation strategy of the hydroelectric plant (e.g., Efstratiadis et al. 2014b, Koutsoyiannis and Ioannidis 2017).

Again, the management of water resources by man through dams and reservoirs also has a positive side for the development of ecosystems and vegetation in particular. Through multipurpose reservoirs combining irrigation and water supply with electrical energy production, freshwater that would outflow to the sea can now be used for organized agricultural use as well as a source of life for all kinds of vegetation that people cultivate in their homes and their cities.

20.7.1.6 Human Societies

The thousands of large dams built globally over the course of the twentieth century are responsible for the displacement and resettlement of tens of millions of human population (Scudder 2012). An extreme case is the Three Gorges Dam (China), which caused the displacement of more than one million people (Jackson and Sleigh 2000). Massive displacements are common in countries like China or India (Fernandes and Paranjpye 1997), but there have also been cases, where displacements caused by a major project, were moderate such as, for example, in Itaipu dam (Brazil), the second biggest hydroelectric project of the world, where 59 000 people were displaced (Ledec and Quintero 2003).

Regarding the effect of the dam on the health of people in the area, cases of stagnant water have been reported to contribute to increases in diseases such as typhoid fever, malaria and cholera in developing countries (Goldsmith and Hildyard 1984), due to the fact that vectors find favourable conditions in the relatively stagnant water of the reservoir. At the same time, dams have been a source of highly reliable energy and clean drinking water, thus helping to develop health infrastructure, increase life expectancy, avoid illnesses associated with poor water quality, often eliminating water scarcity and ensuring a better standard of living overall (Koutsoyiannis 2011a). The positive effects of dams are commonly and mainly utilized by people who live hundreds of kilometres away from its location, significantly exceeding the range of direct environmental impacts. For those people, dams translate into drinking water, cheap and non-intermittent electricity, agricultural products, etc.

The same applies to the inhabitants of the area of the reservoir, but with an important difference. Almost all of the environmental impacts reported are more apparent to them and affect their lives more directly. Overall, depending on how large the impacts of the dam are on the environment and how much the inhabitants of the dam area are culturally connected with it, its construction can be a cause of significant changes in the people's culture itself (Wijesundara and Dayawansa 2011). Yet such changes are not exclusively negative as various cases have been reported internationally in which hydroelectric dams boosted growth, attracting tourism and recreational activities in general, for example, in Spain, Norway, Greece, and the United States (Christofides et al. 2005; Nynäs 2013; Pérez et al. 2013; Smardon 1988). Such cases are abundant and can be found in most countries with hydroelectric infrastructure (Ioannidis and Koutsoyiannis 2017a).

20.7.1.7 Natural and Human History and Landscapes

The process of selecting a suitable site for a dam is challenging and affects the final design in many ways. This is largely guided by economical and technical limitations and can lead to very limited alternatives for the sitting of the dam. In some cases, the final choice might be one that necessitates the inundation of areas of natural and human heritage by the reservoir. In relation to cultural heritage, there are examples of loss of important cultural objects, buildings, archaeological finds, and entire sites that are related to human cultures (Brandt and Hassan 2000). Likewise, many reservoirs have inundated scenic landscapes or places of particular geological value (Tahmiscioğlu et al. 2007).

Nevertheless, in the context of a future where almost all of the energy produced comes from renewable sources, dams are the only type of renewable energy that can create new landscapes without causing industrialization and degradation (Ioannidis and Koutsoyiannis 2017b), which are common problems with solar and wind farms (Frolova et al. 2015; Stremke and Dobbelsteen 2012). In literature related to dams, landscape impact is not considered important, and in fact, dams have both qualitatively and quantitatively less impact on landscapes (Ioannidis and Koutsoyiannis 2017a; Koutsoyiannis and Ioannidis 2017), attract touristic and recreational activities, as mentioned in the previous subsection, and are also considered to create new sites of cultural heritage (Nynäs 2013; Rodriguez 2012).

20.7.1.8 Uncommon Impacts

The focus so far was to report the most common and adequately cited effects of dams on the environment. Nevertheless, it is important to emphasize that dams, as projects that are built all over the globe under different climatic, geographic and cultural conditions, do not have fully predefined and universally identical impacts. Actually, their impacts depend on the design, management and maintenance of the dam as well as on, sometimes unexpected, reactions from nature. Such a case is, for example, the Brokopondo artificial lake (Suriname) whose surface was covered by more than 50% with hyacinths in less than three years (Farnworth and Golley 2013), resulting in increased water evaporation and adverse conditions for fish. Another example of a particular impact from the construction of a dam is the case of the natural lake Urmia (Iran) which almost dried up as the dams upstream of its site were used to divert water for agricultural use (Joudi and Eiraji 2013) without proper water management for the maintenance of the natural lake downstream.

20.7.2 Thermal Power Plants

Thermal power plants use several different resources for energy production, ranging from fossil fuels to nuclear energy. In any case, the turbines use steam to produce mechanical work and thus need water that turns into steam to drive the steam cycle heat transfer. Water is also needed, in much larger quantities, to lower the temperature of steam that remains in the steam circuit after passing through the turbines and condense it back to fluid form. The relatively low energy efficiency figures for thermal plants (Sect. 20.1.2) means that much of the energy produced in the boiler remains in the steam, which explains the large volume of water needed for cooling.

The most important environmental impacts of thermoelectric plants are related to the cooling process and its efficiency. Two major techniques are commonly used in thermoelectric power plants, and they have different, but significant environmental impacts. The first one is called once-through cooling and is described as simply running water through the condensers for one time and then discharging it from the facility (Shuster 2008). This technique is the cause of thermal pollution, as the sudden temperature changes or semi-permanent rise of temperature creates significant problems for aquatic life downstream of the station, which may either be susceptible to sudden changes (thermal shock) or may need certain low temperatures to survive (Pokale 2012).

The second major technique reduces thermal pollution significantly but has the disadvantage of evaporating a percentage of approximately 5% of the water used, thus increasing the water consumption of the plant (Rogers et al. 2013). This is called recirculating or indirect cooling, and its main feature is the use of a so-called cooling tower that dissolves the water into droplets and uses air to lower their temperature. The water drained from the tower is then recirculated in the steam circuit. Another impact is that of carryover salt and other contaminants in the water passing from the cooling tower. To a lesser extent groundwater is also used for the cooling process of thermal plants (Averyt et al. 2011) reducing the reserves and influencing groundwater temperature (in case of reuse).

20.7.3 Marine Energy

As mentioned, marine energy includes various different types such as tidal energy, wave energy and salinity gradient power (osmotic power), and thus several different devices and technologies have been developed to exploit them. In 2020, most of these devices were still considered experimental or pilot, and had not been fully incorporated to national energy generation systems yet (Hamelinck et al. 2012). As a result, the discussion on the environmental impacts of marine energy at that time was based on only a small amount of data on existing marine energy plants and mostly on predicting possible impacts (Frid et al. 2012).

Most of expected impacts are not related to the devices themselves but stem from their manufacturing progress and the auxiliary works. For example, according to Uihlein (2016), the most important impact is from the foundation and mooring works, processes that produce large amounts of CO_2 emission, but also interfere with aquatic life (Langhamer et al. 2010). Additionally, significant CO_2 quantities are also emitted from the manufacturing progress of the devices. As far as the impact of marine energy devices on marine ecosystems is concerned, several possible hazards have been observed during the operation of these devices. These range from direct impact from turbine blades on fish (Hammar et al. 2015) to disorientation and alteration in the behaviour of several species from noise and electromagnetic waves created from the devices.

Meanwhile, several potential impacts of marine energy devices, which have been theoretically considered as important, have not yet been tested on the field, as no large projects of marine energy have been built to provide adequate data. For example, the impact from the alteration of hydrodynamics and kinetic energy in the marine environment (Shields et al. 2011) or the unknown impacts that marine energy devices could possibly have for migrating fish and marine mammal populations (Langhamer et al. 2010), which are similar to the problems that offshore wind farms cause to migrating birds.

20.8 Handling Uncertainty in Water-Energy Systems

20.8.1 Uncertainty Issues in Water-Energy Systems

All aforementioned water-based electric power sources, i.e. hydroelectricity, either as an individual component or integrated within hybrid renewable schemes, as well as wave energy, are driven by randomly varying process across all scales. This irregular behaviour introduces a remarkable degree of uncertainty to the water-related power systems, thus resulting in limited predictability of the natural drivers of energy production. The energy demand is also highly unpredictable (particularly in the long run), as it is strongly influenced by broader socio-economical and geopolitical factors. In this respect, uncertainty is a major element of water-energy systems, which strongly affects their planning, design and management, as well as the cost and sustainability of associated investments.

Typical measures of uncertainty, which are widely used in water resource systems analyses, are reliability and failure probability (sometimes referred to as risk, but the notion of risk has a broader meaning). Reliability is defined to be the probability that a system will deliver a desired performance for a specified period of time, under stated conditions, while the probability of failure is its complement (Koutsoyiannis 2005). Both these probabilistic metrics are associated with a specific desirable performance of the system. For instance, in the case of hydroelectric reservoirs, this is usually expressed in terms of a long-term target energy to be produced at a constant rate throughout a large (theoretically infinite) time horizon, also referred to as firm or reliable energy (Koutsoyiannis and Economou 2003). In a more general context, the target energy is time-varying, thus the system performance, and the underlying uncertainty, are evaluated by contrasting the produced energy against the associated demand.

Nevertheless, in water-energy systems, the analytical determination of reliability and risk through typical statistical approaches (i.e. inference from data, by fitting either an empirical or theoretical distribution), is practically impossible. This has two major reasons. First, such systems are driven by processes exhibiting multiple peculiarities such as periodic change of statistical properties across seasons and auto-dependencies across all temporal scales, which do not allow for applying the major hypotheses of statistical inference (stationarity, independence). Second, the concept of reliability is applied to the system output, i.e. the energy production, not the input. Particularly in hydroelectricity, this output is a highly complex and nonlinear transformation of the input process, i.e. inflow, where a key component of nonlinearity is the regulation of inflows via the storage capacity offered by reservoirs. Additional complexities arise when multiple energy sources are involved (e.g., in case of multireservoir systems as well as hybrid schemes), in which the system's performance is also subject to multiple and conflicting constraints, objectives and human decisions (Koutsoyiannis et al. 2002).

20.8.2 The Stochastic Simulation Paradigm

The well-established approach for evaluating the performance of complex systems is through simulation, generally defined as the representation of a system's dynamics through a computer model. The model is fed with a sequence of inputs to mimic the operation of the system (expressed in discrete time), and produce hypothetical yet realistic outputs, based on which one can evaluate the system's performance by assigning appropriate metrics. In this respect, the reliability of an energy system is easily quantified by counting the number of time steps when the produced energy fulfils the associated demand and dividing by the total length of data.

It is widely accepted that in the context of simulation, the use of synthetic inputs instead of historical records is favoured, because it provides sufficiently large samples (e.g., with length of hundreds or thousands of years) or ensembles of different time series of the same process, to allow the evaluation of a wide range of possible outcomes of the system in study (Efstratiadis et al. 2014a). This is the core of the stochastic (also known as Monte Carlo) simulation paradigm, in which long synthetic series of inputs (e.g. reservoir inflows) are generated from an appropriate stochastic model and then transformed, through the operation model, into synthetic outputs. The use of long synthesized data series allows representation of all aspects of variability of the associated processes (with emphasis to the long-term scaling behaviour as explained below), and proper description of their statistical dependencies in space and time. It also ensures accuracy in the estimation of the desirable statistical quantities, i.e. reliability and risk, in contrast to usually short historical samples. Furthermore, stochastic simulation can be easily combined with optimization, thus offering a robust and generic method for modelling complex systems under uncertainty (Koutsoyiannis and Economou 2003).

Hydrologists and water engineers have long appreciated the usefulness of stochastic simulation–optimization approaches and have applied them in a wide range of water resources applications, including the design and operation of hydroelectric systems (e.g., Pereira et al. 1984, Tsoukalas and Makropoulos 2015, Ubeda and Allan 1994). However, the application of such approaches in hybrid renewable energy systems is rather limited, maybe because the essentially fine temporal resolution of simulations (typically hourly) in addition to the complexity of such systems, introduces significant computational barriers to simulations.

It is worth mentioning that the stochastic simulation paradigm is not restricted to the generation of inputs but can be extended to the energy demand and also captures several other uncertainty issues in water-energy modelling. In fact, uncertainty spans over all aspects of the energy production cycle, which is a sequence of highly complex nonlinear conversions, e.g. rainfall to runoff, wind energy to wave energy, hydraulic energy to mechanical and hence to electrical energy. The associated processes are typically represented through simplified approaches, i.e. models, which are subject to structural and parametric uncertainties. In particular, the internal energy conversion processes are expressed by means of a sole input property, i.e. efficiency, which is a major source of uncertainty. For instance, the efficiency curves of hydro turbines are typically extracted from laboratory models, and they are next adjusted to fit the prototype, by employing empirical corrections; next they are prone to damages and aging of the equipment over time, thus their actual value is by definition uncertain (Paish 2002; Sakki et al. 2020). Nevertheless, a generalized stochastic simulation framework should describe both process and model uncertainties, as is done in a case study of a hypothetical system by Papoulakos et al. (2017).

20.8.3 Insights into Stochastics and Their Application in Water-Energy Problems

The stochastic approach allows for developing a unified perception for all natural phenomena and expelling common dichotomies, such as randomness vs. determinism, or, equivalently, unpredictability vs. predictability. In fact, both randomness and predictability coexist and are intrinsic to natural systems which can be deterministic and random at the same time, depending on the prediction horizon and the time scale. Specifically, the line distinguishing whether determinism or randomness dominates is related to the scale (or length) of the time-window within which the future state deviates from a deterministic prediction by some error threshold ε, and for errors smaller than ε, we assume that the system is predictable only within this time-window (Dimitriadis et al. 2016).

As already mentioned, stochastic approaches enable the generation of (theoretically infinite) ensembles of realizations, while observation of the given natural system can only produce a single observed time series. The literature offers a plethora of models that allow for representing important statistical characteristics of the process of interest, such as its marginal distribution structure and its second (and higher) order dependence structure. By robustly simulating both structures, several important behaviours of the process of interest can be preserved, such as the marginal distribution function along with the diurnal and seasonal periodicities, for example, through marginal transformations (Deligiannis et al. 2016), entropic transformations (Dimitriadis and Koutsoyiannis 2015), or copula-based schemes preserving different distribution functions and autocorrelation structures across seasons and scales (Tsoukalas et al. 2019), as well as the intermittency and the persistence on a wide range of scales (Dimitriadis and Koutsoyiannis 2018).

Depending on the problem of interest, one may focus on different aspects of the processes and put emphasis on the representation of specific characteristics at specific temporal scales. For instance, although the short-term variability is of interest in renewable energy resources (due to its link to intermittency effects and short-term predictions), the long-term variability is more significant in energy management and system sustainability. In fact, all geophysical processes, and apparently the processes that are related to water-energy systems, seem to exhibit high unpredictability at all scales, from the large hydrometeorological to the small turbulent one due to the clustering of events. Interestingly, this clustering behaviour has been first identified in nature by Hurst (1951), while analysing water records from the Nile within the design of projects for the Nile development. However, the mathematical description and analysis of this behaviour through a power-law autocorrelation function is attributed to Kolmogorov (1940).

A recent extensive analysis of a massive number of measurements around the globe of the most vital hydrometeorological processes (Dimitriadis 2017) has shown that all exhibit an intermittent behaviour at small scales quantified by a fractal parameter, and the so-called Hurst phenomenon at large scales, or else Hurst-Kolmogorov dynamics, abbreviated as HK (Koutsoyiannis 2011b). The HK behaviour is characterized by long-term variability (the autocorrelation function decays as a strong power-law and not exponentially; see also O'Connell et al. 2016, and references therein). Therefore, two simple yet robust measures of the inherent short- and long-term uncertainty or variability of a process may be quantified by the fractal and Hurst parameters, which can be both robustly estimated through the climacogram or other climacogram-related metrics (Koutsoyiannis 2019).

20.9 Future Challenges and Directions

Overall, to address the complexity of the water-energy nexus and to pursue a sustainable future in terms of water and energy security, the following research and technology activities will play key roles:

- Addressing the policy fragmentation issue between the two sectors (Hussey and Pittock 2012).
- Pursuing technological innovations and reforms to reduce the water intensity of the energy sector to improve the energy efficiency of the water sector and minimize related environmental impacts.
- Dealing with the lack of water and energy infrastructure and relevant under-investment issues, particularly present in the developing world (Bazilian et al. 2010; Koutsoyiannis 2011a; McCornick et al. 2008).
- Engaging in the design and implementation of large-scale multi-purpose water-energy projects exploiting the available renewable energy resources potential and aiming for reliability and sustainability (Koutsoyiannis 2011a).
- Advancing the understanding of the conflicting and synergistic relationships of the water and energy systems and of the ways they are likely to evolve in the future.
- Extending the data availability to more regions of the world, as in present they are mostly US-dominated (Spang et al. 2014), and strengthening the efforts for systematic data collection and observation platforms (Liu et al. 2017).
- Adopting an integrated modelling approach or a systems approach (Bazilian et al. 2011; Koutsoyiannis 2011a; Newell et al. 2011) dealing with uncertainty, which dominates the natural resources involved (Langhamer et al. 2010); stochastic methods are of great utility in this respect.

Water and energy sources are part of the processes forming the hydrological cycle, and thus, they should entail the same complexity or else the same uncertainty. It is rather crucial then to treat them with similar methods as the stochastic ones implemented for precipitation, wind, and temperature. Furthermore, it is expected that they carry the same degree of unpredictability, and therefore, systems that require management of a large number of such sources (like the hybrid ones) should be optimized through an integrated stochastic simulation–optimization framework. Such an integrated framework, where water, wind, and solar radiation are the sources of energy with water in an additional integrative and regulating role, is highly desirable, given that the exploitation of renewable energy resources should be necessarily combined with large-scale pumped-storage technologies.

20.10 An Example for the Design of a Small Hydroelectric Power Plant

A small hydroelectric power plant is scheduled to exploit the flows of a river. The exceedance probability of the river inflow (Fig. 20.13a) is modelled by the generalized Pareto distribution:

$$P(Q) = 1-F(Q) = (1+Q/10)^{-5} \tag{20.21}$$

where Q is the discharge (m^3/s); P is the exceedance probability of the value Q, and F is the probability distribution function. The hydraulic head of the system is $H = 400$ m, and the overall efficiency is $n = 0.85$. For simplicity, both quantities are considered constant (i.e., independent of flow conditions). Using the above data, estimate:

1. The total water volume (hm^3) and the corresponding annual potential electric energy (GWh).
2. The water volume (hm^3) used from a single turbine with power capacity 16.7 MW and the produced annual electric energy (GWh).
3. The water volume (hm^3) used from a system of two turbines with power capacity 13.3 and 2.7 MW, respectively, and the produced annual electric energy (GWh).

The exceedance probability can be converted to average time by multiplying with a given time interval T. In order to express all quantities of interest on annual basis, we employ $T = 31.56 \times 10^6$ s. We also remark that the inverse of Eq. (20.21) is

$$Q(P) = 10\left(P^{-0.2} - 1\right) \tag{20.22}$$

and its indefinite integral over P is

$$\mathrm{IQ}(P) := \int Q(P)\mathrm{d}P = 12.5P^{0.8} - 10P \tag{20.23}$$

This gives the average inflow as

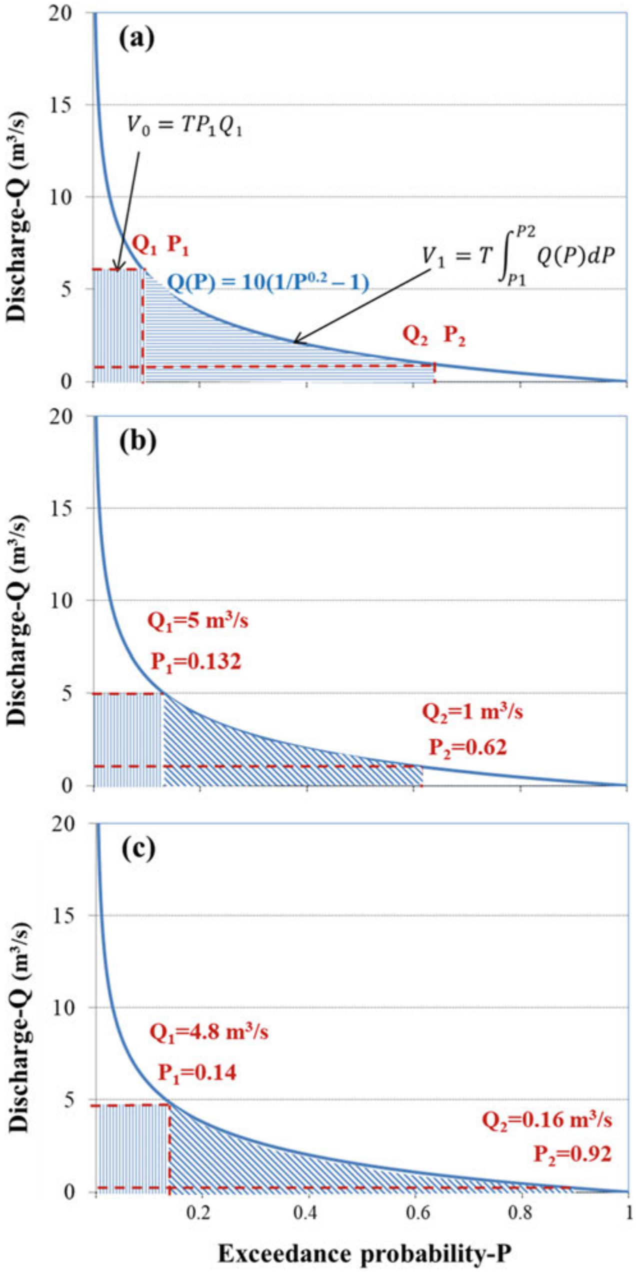


Fig. 20.13 **a** Discharge vs. exceedance probability water volume used in a flow range Q_1–Q_2; **b** water volume used from a turbine 16.7 MW; **c** water volume used from two turbines 13.3 and 3.7 MW

$$E[Q] = \int_0^1 Q(P)dP = IQ(1) - IQ(0) = 2.5(m3/s) \tag{20.24}$$

The answers to questions 1, 2, and 3 now are:

1. For a time period of one year, i.e., $T = 31.56 \times 10^6$ s, this yields an annual volume of $2.5 \times 31.56 = 78.9$ hm^3. According to Eq. (20.4), this corresponds to a theoretical energy production of

$$\begin{aligned} E_{\text{theor}} &= \left(1000\ \text{kg/m}^3\right)(9.81\ \text{m/s})\left(78.9 \times 10^6\text{m}^3\right)(400\ \text{m})(0.85) \\ &= 263.1 \times 10^{12}\text{J} = 73.1\ \text{GWh}. \end{aligned} \tag{2.25}$$

2. From Eq. (20.1), we get that the 16.7 MW turbine has a nominal discharge of $Q_1 = 5$ m^3/s (twice the average inflow). Considering that the lowest discharge at which the turbine operates is 20% of the nominal, we get $Q_2 = 1$ m^3/s. The volume of water that is exploited for a given range of discharges Q_1 and Q_2 is composed by V_0 and V_1 (Fig. 20.13a). In particular, V_0 is the volume passing through the power station with the nominal discharge Q_1, when the inflow is greater than Q_1, and V_1 is the water volume within the operational range Q_1 and Q_2, which correspond to exceedance probabilities P_1 and P_2 (with $P_1 < P_2$). All this amount of water passes through the power station. The two volumes are calculated as:

$$V_0 = TP_1Q_1, V_1 = T\int_{P1}^{P2} Q(P)dP = T(\text{IP}(P_2) - \text{IP}(P_1)) \tag{20.26}$$

where $P_1 = P(Q_1) = (1 + 5/10)^{-5} = 0.132$ and $P_2 = P(Q_2) = (1 + 1/10)^{-5} = 0.620$ (Fig. 20.13b), so that after the calculations IP(P_1) = 1.15 and IP(P_2) = 2.33. Thus, $V_0 = 31.56 \times 0.132 \times 5 = 20.8$ hm^3 and $V_1 = 31.56$ 1.18 = 37.1 hm^3. The volume corresponding to flow values lower than 1 m^3/s is $V_2 = 31.56 \times (2.5-2.33) = 5.4$ hm^3. This amount cannot be used by the turbine. Therefore, the annual water volume to exploit is $V = V_0 + V_1 = 57.8$ hm^3 and the corresponding electric energy production is 192.8×10^{12} J = 53.6 GWh. This system operates 62% of the time (since the lower flow corresponds to probability $P_2 = 0.62$), and the water volume exploited is 73% of the total (i.e., 57.8 out of 78.9 hm^3, as estimated before).

3. We consider that two turbines (A and B) of power 13.7 and 2.3 MW are installed. We find from Eq. (20.1) that the 13.7 MW turbine has a nominal discharge of QA$_1$ = 4 m^3/s and we assume that the lowest discharge at which it operates is QA$_2$ = 0.8 m^3/s (20% of the nominal). The 2.3 MW turbine has a nominal discharge of QB$_1$ = 0.8 m^3/s and a lowest QB$_2$ = 0.16 m^3/s.

For the first turbine operating alone, PA$_1$ = P(QA$_1$) = $(1 + 4/10)^{-5} = 0.186$, PA$_2$ = P(QA$_2$) = $(1 + 0.8/10)^{-5} = 0.681$, so that after the calculations IP(PA$_1$) = 1.395 and IP(PA$_2$) = 2.382. Thus, $V_0 = 31.56 \times 0.186 \times 4 = 23.5$ hm^3 and $V_1 = 31.56 \times 0.988 = 31.2$ hm^3. The volume

Table 20.4 Comparison of examined schemes, with one and two turbines

	One turbine	Two turbines
Installed power capacity (MW)	16.7	16.0 (13.3 + 2.7)
Discharge range (m^3/s)	1–5	0.16–4.8
Operation time (%)	62	92
Water volume exploited (hm^3)	57.8	62.3
Water volume to total (%)	73	79
Energy production (GWh)	53.6	57.7

corresponding to the period in which the discharge is lower than 0.8 m/s is $V_2 = 31.56 \times (2.5 - 2.382) \times 0.8 = 3.0$ hm^3 and this is not used by the turbine. The annual water volume exploited is and $V = V_0 + V_1 = 54.6$ hm^3 and the corresponding electric energy is 50.6 GWh. The turbine operates 68% of the time and the water volume exploited is 69.2% of the total.

For the second turbine operating alone, $PB_1 = P(QB_1) = (1 + 0.8/10)^{-5} = 0.924$, $PB_2 = P(QB_2) = (1 + 0.16/10)^{-5} = 0.681$, so that after the calculations $IP(PB_2) - IP(PB_1) = 2.494 - 2.382 = 0.112$. Thus, $V_0 = 31.56$ $0.681 \times 0.8 = 17.2$ hm^3, $V_1 = 31.56 \times 0.112 \times 0.16 = 3.5$ hm^3. The volume corresponding to the period in which the discharge is lower than 0.16 m/s is $V_2 = 31.56 \times (2.5 - 2.294) \times 0.16 = 0.03$ hm^3 and this is not used by the turbine. The annual water volume exploited is and $V = V_0 + V_1 = 20.7$ hm^3 and the corresponding electric energy produced is 19.2 GWh. The turbine operates 92% of the time and the water volume exploited is 26.3% of the total.

The combination of the two turbines exploits a flow range from 0.16 (the lowest of the small turbine) to 4.8 m^3/s (the sum of the nominal discharges of the two turbines). Thus, $P_1 = P(Q_1) = (1 + 4.8/10)^{-5} = 0.141$, and $P_2 = P(Q_2) = (1 + 0.16/10)^{-5} = 0.924$ (Fig. 20.13c). The annual water volume exploited is $V = 62.3$ hm^3 and the corresponding electric energy is 57.7 GWh. This system operates 92% of the time and the water volume exploited is 79% of the total.

A summary of the two schemes is given in Table 20.4. An interesting outcome is that the use of mixed turbines, with a little lower total power capacity (−4%), ensures higher annual energy production (+8%), since the different turbines can exploit a wider range of flows. For this reason, the combined system operates 92% of time, while the single-turbine system remains out of operation during the low-flow period (about four months per year, on average).

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