CHAPTER 8

Hydropower

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1 Introduction

Hydropower has been used by mankind for centuries, with early references dating back to the Han Dynasty in China and the ancient Greeks. Whilst it was then predominately used to grind grains, it later became a source of power for spinning frames to spin cotton during the industrial revolution.

Turbine technology innovations in the nineteenth century paved the way for modern uses of hydropower. In 1827, the French engineer Benoît Fourneyron developed the first waterwheel that is referred to as turbine, capable of producing approximately 6 horse powers or 4.5 kW. Later versions of his turbines spread across Europe and the United States. The most commonly used turbine, the Francis turbine, was developed shortly after, in 1849, by British-American engineer James Francis. In the late 1870s, American inventor Lester Allen Pelton invented an impulse water wheel, the Pelton turbine.

These innovations enabled to utilise hydropower for electricity generation whereby the first installation lit a single light bulb in 1878 in Northumberland, England. Many more followed, first in Europe and North America and by the turn of the century also elsewhere around the globe. During the twentieth century, increasingly larger hydropower stations were developed, and some projects' purposes extended from electricity generation to flood control and irrigation. In 1936, in the middle of the Great Depression, the Hoover Dam started production with an initial capacity of 1345 MW.

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M. Hafner, G. Luciani (eds.), *The Palgrave Handbook of International Energy Economics*, https://doi.org/10.1007/978-3-030-86884-0_8

Today, hydropower is the source of the largest power stations in the world, the Three Georges Dam in China, with a capacity of 22.5 GW, and the Itaipu Dam at the border of Brazil and Paraguay, with a capacity of 14 GW. Globally, with over 4000 TWh generated in 2018, hydropower accounts for approximately 16.3 per cent of electricity generation and installed capacities exceed 1000 GW (International Energy Agency 2018). This makes it, at the time of writing, by far the most important renewable energy source, providing approximately 67 per cent of all electricity generated from all renewable sources (International Energy Agency 2018). Hydropower stations are located all over the world and in all climate zones as Table 8.1 illustrates. However, hydropower stations are predominantly installed in regions with favourable topographies.

Whilst in the developed world the best and most suitable sites for hydropower generation have long been exploited, there remain significant hydropower potentials in the developing world, in particular in Africa. There has been substantial hydropower growth in the last decades in East Asia, almost exclusively due to growth in China, which has the highest installed capacity and production of any country. Altogether, hydropower has been a competitive source of electricity generation for over a century, yet it requires certain geographical features, which will be explored in more detail later. As a result, suitable locations in the developed world have mostly been exploited, and during the last decades, growth has taken place primarily in the industrialising economies.

One can differentiate between three hydropower generation types: run-of-river, hydro storage and pumped storage. The following chapters describe the characteristics of the three technologies. The generation in all three types follows the same principle, as water is used to turn one or multiple turbines. One can calculate the power output of a hydroelectric turbine with the following formula:

$$P = \eta \times \rho \times q \times g \times h$$

Table 8.1 Installed hydropower capacity by regions (2016)

Region	*Installed hydropower capacity (in GW)*	*Share of total*
Africa	22.3	2.1%
Middle East & North Africa	18.1	1.7%
Latin America & The Caribbean	140.4	13.2%
North America	171.3	16.1%
Europe	259.6	24.4%
South & Central Asia	63.8	6.0%
East Asia	336.2	31.6%
South East Asia & Pacific	51.1	4.8%
Total	1064	100%

Source: World Energy Council

where P is the power output, η the efficiency of the turbine (generally between 0.8 and 0.95), ρ the density (approximately 1000 kg/m^3 for water), q the site-specific water flow in m^3 per second, g the gravity (9.81 m/s^2) and h stands for the hydraulic head, that is, the falling height in metres.

2 Run-of-River

Run-of-river hydroelectricity describes hydro generation plants using the water stream of a river to generate electricity without any, or only limited storage, referred to as pondage. The volume of water flowing down the river and the drop of the riverbed level determine the amount of electricity that can be generated. The larger the drop of the riverbed level and the volume of water, the greater the potential energy that can be converted into electricity. Run-of-river power plants usually divert water from the river into a canal or pipe that directs the water to the powerhouse. The so-called penstocks lead the water through turbines which generate electricity. Afterwards the water flows downstream through pipes or canals referred to as tail race back into the river.

Due to the fact that run-of-river power plants do not store water in a reservoir, they are somewhat limited in their scalability and flexibility. Capacities range from micro installations with a capacity of only a few kilowatt (kW) to large-scale plants, which may have a capacity of up to several hundred megawatt (MW). Typically, plants with a capacity of 100 kW up to 1 MW classify as mini installations, with plants up to 10 MW (or up to 50 MW depending on national jurisdiction) are labelled as small and anything larger as large-scale plants. Generally speaking, large-scale plants between 10 and 1000 MW capacity dominate global installed capacities and production volumes.

The lack of water storage makes run-of-river power plants dependent on river flows that can have significant daily and seasonal fluctuations. Plants by alpine rivers, for instance, experience considerable larger production volumes in spring and summer months following the snow melt (see Fig. 8.1). In other parts of the world, freshets, monsoon seasons or other weather phenomena such as El Niño can cause similar production fluctuations in other months. Run-of-river power plants are therefore an intermittent power generation technology that is only partially dispatchable and cannot always adjust its power output according to the demand, as, for instance, hydro storage plants.

Since run-of-river power plants do not require large dams that store water, construction is simpler and avoids accompanying issues that are associated with the construction of dams (see next section).

The environmental impact of any hydropower plant ought to be regarded on an individual basis as it depends on the location as well as the type and size of the plant. Generally speaking, run-of-river power plants have a lower environmental impact on human and aquatic life than hydro reservoirs or pumped-storage plants, given that no dam construction and flooding of land areas is required. Nevertheless, run-of-river power plants still have a negative impact

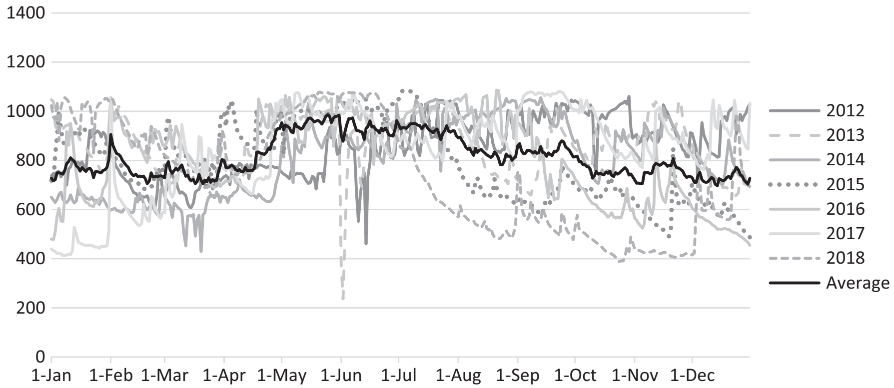

Fig. 8.1 Production profile (daily average produced megawatt hours) of a run-of-river power plant in Switzerland shows yearly and seasonal variations. (Source: Authors' elaboration on Axpo Holding AG data)

on (often fragile) river ecosystems. The plant represents a physical barrier for fish populations, especially migratory fish, and depending on turbine design and operating mode, passage can often be lethal or sublethal for the fish.[1] In recent decades, improvements have been made in terms of turbine designs and bypassing options such as fish ladders, yet legislative requirements vary significantly by country or jurisdiction.

Run-of-river power plants have very long lifetimes. Some key equipment such as turbines last about 25 years before they are replaced, yet the power plant typically has a long lifetime of approximately 80 years. Often power plants approaching the end of their lifetime are modernised rather than dismantled, since suitable locations are limited and hydropower is still an economic source of renewable energy today. Some of the older hydropower plants, especially in Europe, are listed buildings of cultural heritage.

3 Hydro Storage

Hydro storage power plants typically use a dam to store water in a reservoir. The reservoir acts as energy storage, using the gravitational potential energy of water at higher elevation. To generate electricity, gates let water flow into penstocks, which in turn lead the water to one or multiple turbines in the powerhouse. Afterwards the water flows downstream into a basin and/or river. In essence, the general concept works like in a run-of-river power plant with the key difference that the water flow is controlled by the plant operator. This means that hydro storage is—unlike run-of-river hydro—a dispatchable source

[1] See Anderson et al. (2015) for a detailed analysis of run-of-river hydropower's impact on ecological conditions of rivers.

of energy. Operators can choose the quantity and timing of electricity to be generated within given regulatory restrictions.

Hydro storage power plants and dams can be colossal in size and capacity and form some of the largest man-made structures on earth. The Three Gorges Dam in China, for instance, is the largest power station in the world with an installed capacity of 22,500 MW. In terms of electricity production, only the Itaipu Dam on the border of Brazil and Paraguay surpasses the Three Gorges Dam (depending on hydrological conditions) with recorded production volumes of over 96 TWh annually in the late 2010s. Aside those enormous-sized hydro storage plants, there are also comparably small hydro storage installations of only a few MW. Micro or mini hydropower plants, however, usually do not classify as hydro storage but as run-of-river.

The operational nature of hydro storage power plants differs significantly. Some, such as the two named above, produce baseload power and have comparably high capacity factors. Others are peak-load power stations with much lower capacity factors and operate only in times of high demand or high prices. The size of reservoir, the water flow into the reservoir and the turbine capacity are factors that determine how a hydro storage power plant operates. Depending on the site, further factors such as legally required minimal water flows and reservoir levels also play a role.

Most hydro storage power plants in liberalised European power markets function as peak-load plants. During spring and summer months, following the snow melt, the reservoirs fill up. Peak demand, and with it high prices, usually occurs in Europe during winter months, which is why operators of hydro storage power plants discharge the majority of water then (see Fig. 8.2: Weekly water levels of Swiss hydro reservoirs (in per cent) illustrate the seasonal usage of hydro storage plants in the Alps. Source: Authors' elaboration on Swiss Federal Office of Energy data). Given that each unit of stored water can only

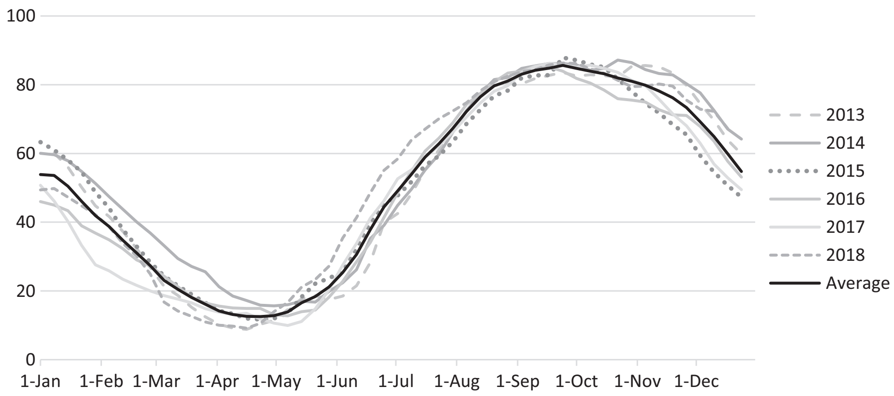

Fig. 8.2 Weekly water levels of Swiss hydro reservoirs (in per cent) illustrate the seasonal usage of hydro storage plants in the Alps. (Source: Authors' elaboration on Swiss Federal Office of Energy data (2019))

be discharged once, the discharging, that is, selling of hydro storage, reflects a bet against higher prices in the future. A certain amount of water (site-specific, see formula mentioned earlier) in an upper reservoir is equal to a call option of generating a unit of electricity. The opportunity costs of releasing water are equal to the expected future value of electricity. Hydro storage power plant operators use modern option pricing theories to optimise the dispatch of their plants. Put simply, operators try to serve the highest priced hours a year with the limited amount of water available in their reservoirs. Unlike other generators who bid with their marginal costs on energy-only markets, the dispatch of hydro storage power plants is not marginal cost based. Instead, operators use shadow prices—reflecting the marginal costs of additional alternative (thermal) power plants—to place their bids on the market.

Hydro storage power plants require certain geographical and geological features. Usually they are located in mountainous areas where elevation levels of river drop sharply, and the topography enables storing water in a reservoir. The reservoirs of hydropower plants often cover vast areas of formerly dry land. The construction of dams and creation of reservoirs thus have far-reaching consequences for river ecosystems and surrounding areas. Reservoirs do not only flood large areas of land, converting valleys into lakes, but also alter the river ecosystem further downstream. Natural seasonal floods no longer occur and altered flow rates lead to losses in biodiversity as well as changes in sedimentation, as dams may hinder the flow of sediments downstream. There is also an ongoing academic debate on the greenhouse gas emissions (first and foremost methane) of reservoirs, especially in tropical climates, due to microbial decomposition of organic material in the water under anaerobic conditions.[2]

It is important to note at this point that the construction of (large) dams and reservoirs has an impact on not only the natural environment but also the people living there. At the turn of the century the ‘World Commission on Dams’, a global governance forum researching controversial issues of large dams under patronage of Nelson Mandela presented a final report (World Commission on Dams 2000). A key motivation was to solve and prevent human conflict associated with the construction and use of dams especially in developing countries. The final report highlights inter alia that in too many cases an unacceptable price in social and environmental terms has been paid for the considerable benefits of dams by communities downstream and by people displaced, whose number is estimated at 40–80 million (World Commission on Dams 2000).

Just like run-of-river power plants, hydro storage power plants have very long lifetimes of approximately 80 years. Hydromechanical elements usually have shorter life spans and are replaced accordingly, whilst the structure of the dam can have a longer lifetime than 80 years, depending on the design. Regular assessments of the structural safety of dams are essential, given catastrophic consequences of a dam failure. In Europe, a governing body grants operators

[2] See Prairie et al. (2018) for a detailed discussion on greenhouse gas emissions from reservoirs.

concessions that typically cover a period of 25–75 years (Glachant et al. 2014, p. 21). Once a hydro storage power plant with dam and reservoir is built, it is usually there to stay. Dismantling a hydroelectric dam with a reservoir is a complex and costly task. In Europe, dams approaching the end of their lifetime undergo a modernisation in most cases and only comparably small dams have been removed thus far. Hydropower dam removal has been more significant in North America, yet no dams with considerable large power productions have been dismantled to date.

4 Pumped-Storage Hydroelectricity

Pumped-storage hydropower plants use two or more reservoirs at different elevation levels to store electricity in form of gravitational potential energy of water. During low-priced hours, water is pumped to a reservoir with a higher elevation level, and in times of high prices, it is discharged to generate electricity. The power generation process is the same as for hydro storage power plants, the only difference being that discharged water is collected in a reservoir at lower elevation.

Since the pumping process consumes electricity, pumped-storage hydropower plants both consume and produce electricity. Pumped hydro is to date the only (grid scale) economically viable and mature form of storing electricity, yet significant progress has been made in different battery technologies in recent years. The round-trip efficiency (pumping up water and discharging it to generate electricity) of pumped-storage hydropower is typically between 70 and 80 per cent (Rehman et al. 2015).

In general, pumped-storage hydropower plant reservoirs tend to be smaller than those of hydro storage power plants without a pumping component. This is due to different use cases. Whereas many hydro storage power plants serve as seasonal storage with reservoirs filling up during spring and summer months, pumped-storage plants function first and foremost as daily or weekly storage units. There are, however, also pumped-storage plants with comparably large reservoirs and conventional hydro storage plants that have had a pumping component and lower-elevation reservoirs added. Economies of scale apply to pumped-storage hydropower plants, which are why installations are commonly large scale, with typical capacities between 1000 and 1500 MW, the largest installation being the 3003 MW Bath County Pumped Storage Station in the United States. Globally, installed pumped-storage hydro capacity reached approximately 160 GW at the end of 2018, accounting for over 94 per cent of installed energy storage capacity (Henley 2019).

The aforementioned location constraints of hydro storage power plants apply also to pumped-storage installations, yet reservoirs tend to be smaller. Consequently, pumped-storage hydropower plants are typically located in mountainous areas and have an elevation difference between reservoirs of a few hundred metres. The first pumped-storage hydropower station was developed

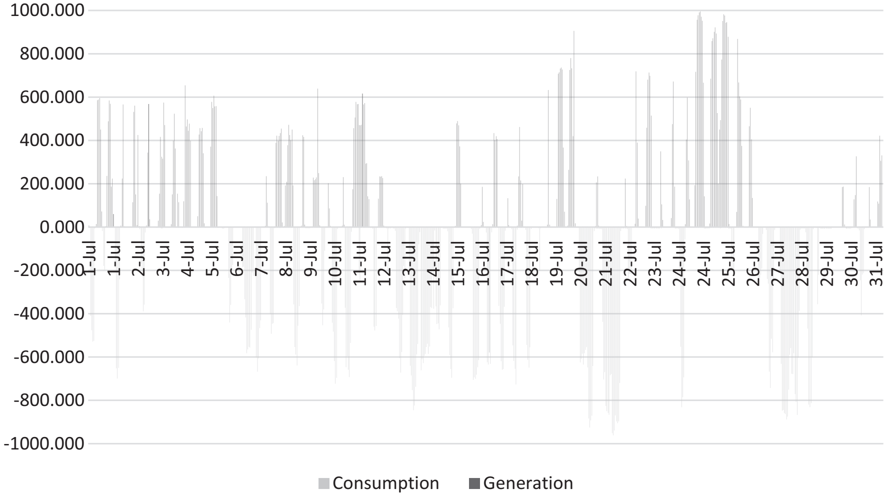

Fig. 8.3 Monthly pump/generation profile of a pumped-storage hydropower plant in MWh. (Source: Authors' elaboration on Axpo Holding AG data)

in the Swiss Alps over 100 years ago. Today, China, Japan and the United States are the countries with the highest installed capacities of pumped storage.

Economically, pumped-storage hydropower plants use price spreads on electricity markets. During low-priced hours (e.g. during night-time, weekends or at times of excess supply), water is pumped up in the upper reservoir, and during high-priced hours, it is discharged to generate electricity (see Fig. 8.3). The greater the price spreads on a given market, the higher the profitability of pumped-storage power plants. This operating nature contributes to balance markets, especially at high penetration rates of intermittent renewable energies, which is a matter that will be explored in more detail in the following section.

Given the similarities of conventional hydro storage and pumped-storage power plants, environmental concerns of conventional hydro storage (see above) apply also to pumped-storage installations. In addition, pumped-storage power plants have been criticised for the fact that they consume more electricity than they generate (unless there is a considerable natural inflow). This criticism neglects the fact that pumped-storage plants generate electricity during times of peak demand that would otherwise be covered by dispatchable conventional fossil fuel-based generation sources. Indeed, operators of pump-storage power plants use shadow prices of additional conventional fossil fuel-based power plants in the merit order for their dispatch strategy and bids on power markets. There is little doubt amongst experts that energy systems with (very) high penetration of intermittent renewables require storage solutions such as pumped storage and batteries, highlighting the importance of pumped-storage hydropower plants for decarbonising power systems.

5 Role of Hydropower in Generation Portfolios and Flexibility

Hydropower has been an economically viable generation technology for over a century. The role of hydropower in countries' generation portfolios has therefore developed slowly over time without the radical changes observed in other renewable energy capacities. Wherever the natural environment enabled the use of hydropower in the industrialised world, then hydropower capacities were often deployed. Today, hydropower benefits from the fact that it is a renewable and emission-free power generation technology, something that was not deemed particularly relevant in the early days of hydropower development. The role of hydropower in countries' generation portfolios is therefore typically set by how well a given country is suited for hydropower. Some countries such as Norway, Albania or Paraguay cover virtually all or even more than their domestic electricity needs by hydropower sources.

It is fair to note that the role of hydro in a generation mix is more a result of the natural environment than of policy decision, as hydropower typically offers an economically viable and sustainable source of power if suitable waterways with considerable elevation drops are available. As a result, hydropower potentials in developed nations are largely exploited, and global hydropower growth is less substantial than that of other renewable energies such as wind and solar photovoltaics (PV). China accounts for most of the global growth of hydropower and has a share of approximately 19 per cent in its generation mix (International Energy Agency 2018). In the United States, around 7 per cent of the power generation comes from hydropower sources, and in the European Union (EU-28), it is approximately 10 per cent with considerable differences between member states (Eurostat 2019; International Energy Agency 2018).

As aforementioned, hydropower plants can be used to meet near baseload demands with high capacity factors. They can also be designed to cover peak demand with high installed capacities and lower capacity factors and everything in between. Be that as it may, even when the share of hydropower is small in any given country, the flexibility of hydro storage and pumped-hydro is often crucial for the stabilisation and balancing of the power grid. Hydro storage and pumped-storage plants can ramp up production within seconds to react to market signals and grid demands. In other words, the flexible plants help to keep the frequency stable at sudden changes of supply or demand, by adjusting the power output accordingly. In a decarbonising world with increasing penetration of variable renewables in power grids, this flexibility is critical for security of supply. Pumped-hydro flexibility is twofold and comes handy, as it not only can provide additional generation capacity during times of high demand but also acts as a consumer to store surplus electricity. Whilst pumped hydro functions as a daily storage unit in most cases, conventional hydro storage plants typically serve as seasonal storage units. The use case therefore differs from the one of grid-scale batteries, which have been experiencing significant cost reductions over the last years, but are adapted only for shorter flexibility. Aside batteries, hydro storage is currently the most flexible generation technology that can follow the load without the efficiency losses of conventional thermal power plants at lower loads. Power systems with considerable shares of flexible hydro units can therefore integrate variable renewable production more efficiently.

6 Hydropower Costs and the Financing of Hydropower Plants

Construction costs for hydropower plants are very site-specific. Large and small-scale plants can differ significantly in their costs per unit of installed capacity and per unit of electricity generated. Yet not just the size of the power plant but also the legal/regulatory requirements (e.g. fish passages) and the location (e.g. remote mountainous areas) are key factors that determine the costs of a specific plant and may vary drastically from site to site. Anyhow, compared with other power generation technologies hydropower plants are typically characterised by high to very high capital expenditures (capex). The International Renewable Energy Agency (IRENA) sets the installation cost range for large hydropower at 1050 to 7650 USD_{2010} per installed kW and slightly higher for smaller plants as they are less likely to profit from economies of scale (IRENA 2012).

In contrast to the high capex, the operating expenditures (opex) of hydropower plants are very low, since the fuel, that is, the water, is usually free. The operating costs of hydropower plants stem primarily from maintenance costs of mechanical equipment and labour costs for operating the plant resulting in very low overall opex.[3] IRENA describes the annual operation and maintenance costs of large hydropower projects as 2 to 2.5 per cent of investment costs per installed kilowatt and slightly more for smaller installations (IRENA 2012). Put together, hydropower can be a very economic source of electricity when analysing the costs over a lifetime. In this context, scholars refer to the so-called levelised costs of electricity (LCOE) that describe the average lifetime costs of electricity generation. Following IRENA's hydropower installation and operating costs, the agency gives large hydropower an LCOE range of 0.02 to 0.19 USD_{2010} per kilowatt hour (and up to 0.27 USD_{2010}/kWh for small hydropower) assuming a 10 per cent cost of capital (IRENA 2012).

The relatively high capital expenditures (capex) combined with a typically rather long lifetime of hydropower plants make investments in hydro power difficult. During the first wave of hydropower, in the first half of the twentieth century, many hydropower plants were built by state owned companies or quasi monopolies. Nowadays most hydropower plants have to be financed by privately owned companies with no or very limited subsidies or securities from governments or states. However, financing infrastructure investments with

[3] It should be noted that this is subject to varying national jurisdictions that may increase operational expenditure, for instance, by charging hydropower plant operators for the use of the water.

high capital expenditures, long lifetimes and uncertain future revenues can be challenging.

Other renewable energy sources such as wind and photovoltaic also have high capex compared to their operating expenditures. But similar to hydropower plants, many governments and states helped building the first wave of wind and photovoltaic plants with subsidies such as fixed tariffs or with other forms of securities for future revenues. Over the last decade, most governments and states reduced securities they offer for new wind and photovoltaic plants. With this reduction of subsidies and securities, the market developed new instruments for financing renewable plants, first and foremost power purchase agreements. However, these power purchase agreements typically have a duration of only 10 years. For power plants with lifetimes of approximately 20 years, a security for the first half of their duration is typically enough to enable private financing. But for hydropower stations with significantly longer lifetimes, power purchase agreements with a duration of 10 years do not cover enough uncertainties regarding future revenues to allow for significant private investments.

7 Outlook for Hydropower

As a renewable and clean generation technology, hydropower should continue to play an important role in future low carbon power systems. Even though further sites for hydropower deployment are limited in the developed world, there are significant untapped technical potentials in the developing world, especially in Africa (Henley 2019).

Unlike other renewable energy technologies such as wind and PV that experienced substantial technical innovation during the last two decades, no such drastic innovations or cost reductions can be expected for hydropower. However, it can be expected that the benefits of flexible hydropower technologies will be challenged by other storage technologies such as batteries. Moreover, one can assume that the benefits of renewable run-of-river plants will be challenged by other renewable technologies.

However, at a broader picture one can assume that geography will always be a driving factor behind renewable energy sources. In windy regions, some form of wind power plants will be used (as it was already used for at least two centuries), sunny regions will try to harvest the power of the sun, and in wet and mountainous regions, some form of hydropower will continue to play an important role in the power generation.

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