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Hydro Energy

Overview of hydro energy technologies

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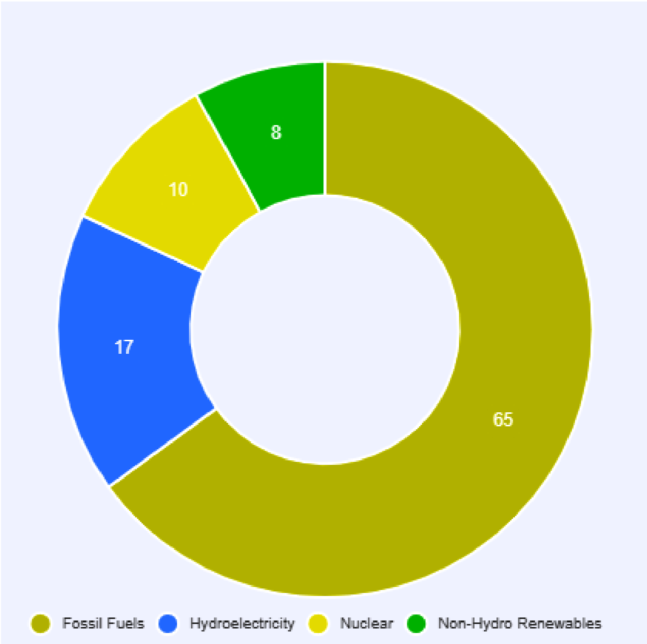
Basic definitions

Water power, concentrated in river flows or mountain reservoirs, has long been used by mankind to extract energy. From primitive water wheels, the technology developed until - by the second half of the nineteenth century - the generation of electrical energy from water streams via hydro turbines was achieved. Hydropower, along with fossil fuels, became one of the main sources of energy for the industrial revolution and today remains an essential element of modern energy, providing about 7% of primary energy and about 17% of electricity worldwide (Fig. 1 and 2).



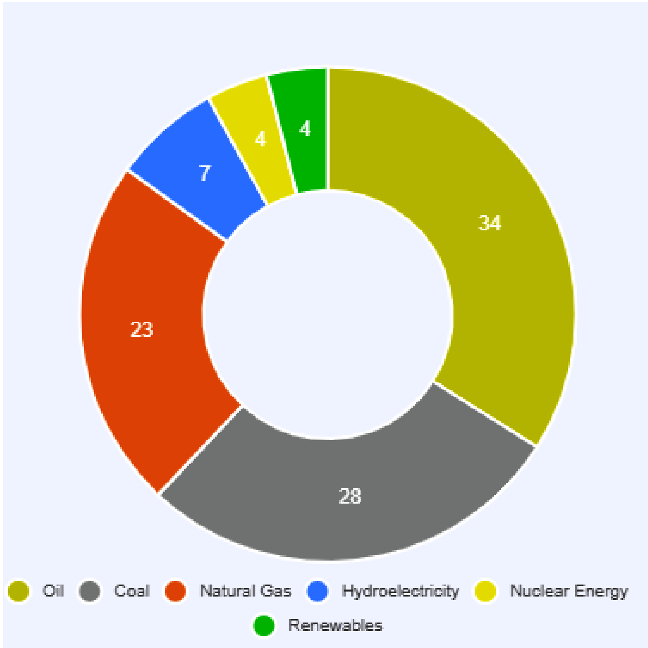


Fig. 1–2. Left–World electricity net generation in 2016, %. Right–Primary Energy Consumption by Fuel in 2017, %
Source: Based on Data from U.S. Energy Information Administration (Apr 2019), BP Statistical Review of World Energy June 2018

Despite the enormous technical advances in various areas of human activity over the 130-years plus since the advent of hydroelectricity, the process of converting the energy of water flow into electrical energy has not changed much. Electricity generation is carried out by a generator, the rotor of which is connected to the shaft of a hydro turbine, that rotates under the pressure of a water stream. A detailed study of this process and numerous engineering improvements led to the development of specialized turbines. The type of turbine used is determined by the characteristics of the water flow, and is supported by infrastructure in the form of dams, tunnels, outlets, reservoirs,

Fig. 3-4. On the left - India. Shivasamudram hydropower plant is one of the first hydropower plants in Asia, 1902, increase from 700 KW to 42MW. Right – Austria Nussdorf weir.(1899) and Nussdorf power station (2005) 28.14 GWh/year

etc. to improve the efficiency of electricity production. This process is further aided by implementing advancements made in electrical engineering and methods of process control. Today, Hydroelectricity is the most mature, tested and successful technology for generating electricity from renewable sources.

There are three main options for hydropower facilities [1,2,3]: designs with a dam and a reservoir - storage schemes; designs using natural riverbeds that provide reliable overflow - Run-of-river schemes and Pumped storage schemes. Additionally, this list may include the use of tidal water flow - tidal power, now more commonly referred to as ocean energy.

The use of various schemes of hydropower facilities is dictated by the natural landscape, seasonal features of each specific region, standard requirements for ensuring safety, reliability, efficiency, and the functional purpose of the facilities. The use of storage schemes mitigates the effects of seasonal fluctuations and increases the reliability of power systems in general. Pumped storage allows for the continued operation of power systems during peak loads or to compensate for the suspension of electricity generation by other sources. Cascade systems, which feature a succession of hydroelectric stations downstream of large rivers, have become quite widely used [1]. This configuration significantly optimizes the use of water energy and improves the performance of hydroelectric stations. For example, on the Austrian Danube about a chain of around a dozen large power plants are located, most of which have an annual output of more than 1 million MWh of electricity, and includes the Altenwörth power plant hydroelectric station producing over 2 million MWh [4].

Hydropower plants can be small (with a capacity of up to 10 MW), medium (with capacities ranging from 10 to 300 MW), or large (exceeding 300 MW); however, there are also more detailed classifications with markedly different characteristics [1,5].

There are three main types of water turbines: Francis turbines, the most versatile and common; Kaplan turbines, which are suitable for large water flows, but with a small pressure; and Pelton turbines, that are in turn used at high pressures and low flows. Pumped storage plants most often supplement existing hydroelectric stations with a special upper or lower reservoir outside the main flow. Such schemes are called “open-loop” systems, in contrast to closed-loop systems with two independent reservoirs [1].

Hydro energy resources

Aided by modern technological advances, our planet has a large hydro energy potential. According to [6], technically feasible hydropower potential amounts to about 16,000 TWh/year, while global electricity production in 2017 was at just over 25,500 TWh [7]. Thus, hydropower is able to satisfy more than half of the global electricity demand, even when taking into account more conservative estimates of economically exploitable potential that can reach 50-80% of the technical potential, depending on the situation on the energy market.

The largest technically exploitable hydro potential is available in Latin America and North America, as well as in Europe, where currently 25-50% of the hydro potential is being utilized [1,6,7,8]. However, in the countries of Asia, and especially Africa, there also exist very large untapped hydro resources.

The distribution of water resources in different countries is extremely uneven. The size of the country, the presence of mountain ranges and basins of large rivers play a big role in determining hydro power potential. Several countries have technically exploitable hydro capability exceeding 500 TWh/year, these are China, Russian Federation, USA, Brazil, Canada, the Democratic Republic of Congo and India. Of these, China leads with 2,474 TWh/year [6]. The top 10 countries with the highest technically exploitable potential, and the level of its use, are presented in Fig. 5.

A number of relatively small countries — Albania, Nepal, Paraguay, Zambia, and others — generate virtually all of their electricity from hydro-resources [8]. In Norway, this figure exceeds 90%, and in Brazil, around 70%.

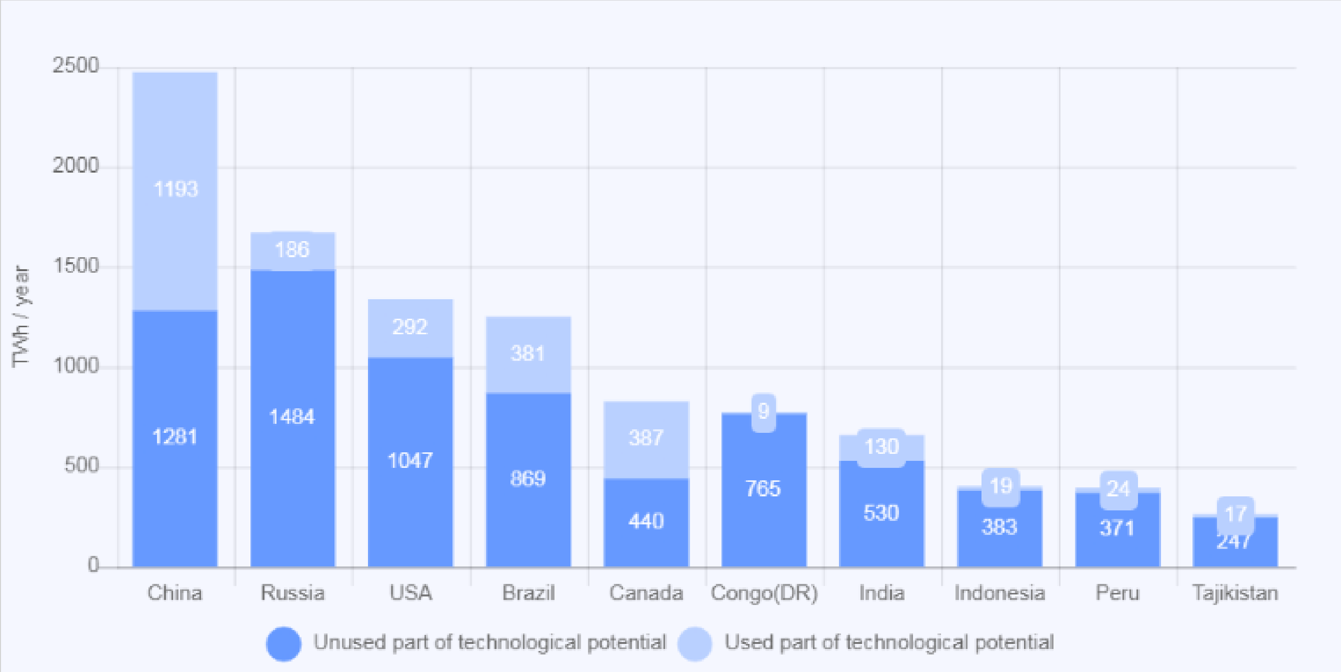


Fig.5. Top 10 countries with maximum technically exploitable capability of hydro energy (Twh/year) and the share of its use in 2016 (%)

Sources: Based on Data from 2010 Survey of Energy Resources World Energy Council 'Used by permission of the World Energy Council, London, www.worldenergy.org;IRENA (2017), Renewable Energy Statistics 2017, The International Renewable Energy Agency, Abu Dhabi

In China, the main water resources are concentrated in the south-west of the country in the mountainous regions of the Himalayas, Tibet and Kunlun, and in the basins as on the largest rivers of the Yangtze and the Yellow River, which draw their potential from these mountain ranges [9]. The main hydroelectric power stations in China can be found here. The cascade of hydroelectric power plants on Yangtze River, which has more than 700 tributaries, after the completion of all planned construction work, will consist of 9 large hydroelectric power plants with a total capacity of 80 GW. The configuration includes the world's largest hydropower plant, the Three Gorges Dam, operating since 2012, with a capacity of 22.5 GW [10, 11,12].

In Brazil, the northern regions of the country in the Amazon area and its tributaries have the greatest hydro potential. More than 40% of the country's hydro resources are concentrated here, of which about 23% have been developed [13,14,15]. However, most of the hydroelectric power plants in Brazil were built in the south of the country to supply the most economically developed region. This includes the largest hydroelectric station in Brazil, and the second largest in the world, the Itaipu Dam [16] with a capacity of 14 GW, which began operating in 1984.

Fig. 6-7. The two largest hydropower plants in the world. Left the Three Gorges Dam, China, 22.5 GW. Right the Itaipu Dam, Brazil, 14 GW

Significant hydro resources in Canada are represented in all its regions, with Quebec in the eastern part of the country, and British Columbia in the west, having the greatest potential [17].

More detailed information on hydropower resources of the countries of the world can be found in the list below [18-42].

Mainstream technologies

Hydroelectric power plants are designed to convert the kinetic energy and potential energy of water flow into the mechanical energy of rotation of the turbine shaft, which is driven by the pressure of water flow on turbine blades. The useful power output of a turbine in watts of a particular construction depends on two main variables - volumetric flow rate per second and the elevation difference between the outlet and inlet surfaces in meters.

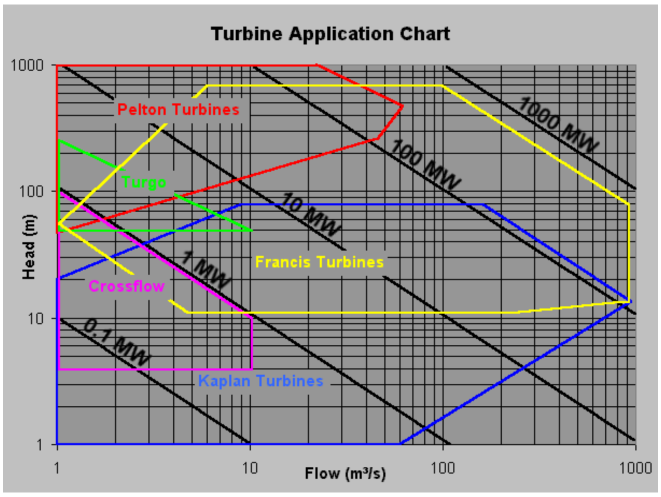
By adjusting these parameters, it is possible to ensure the specified output power of the turbine and, accordingly, the expected level of power generation by the generator, the rotor of which is directly connected to the turbine shaft. Modern turbines can provide more than 90% mechanical efficiency of energy conversion. It was noted above that water turbines are divided into several types, depending on the output of power from small, with a capacity of less than 10 MW to large, with a capacity exceeding 300 MW. Turbines, in turn, are also divided into reaction turbines and impulse turbines. Reaction turbines receive energy mainly via water pressure; impulse turbines, via kinetic energy of the water jet.

Despite the variety of designs of water turbines, three of them - the Francis turbine, the Kaplan turbine, and the Pelton turbine are the most used; each being named after its creator (Fig. 8).

Fig. 8. Three main types of modern hydro turbines

Turbines are designed for specific heads and flows. Working ranges for most of the main types of turbines are shown in Fig. 9 [43]. The most versatile, and therefore most common, is the Francis turbine, which is suitable for pressures from 50 to 700 meters and average flow speeds [4]. Before water enters the turbine, it is pre-unrolled in a spiral pipe and directed tangentially to adjustable turbine blades (Fig.10.), after which the water flows down through a special drainage system.

The Kaplan turbine, as can be seen in Fig. 9, is effective for low pressure and large streams of water. The turbine looks like a propeller with adjustable blades (Fig.8.). The vertical turbine shaft is connected to the generator shaft. The water pressure decreases between inlet and outlet from the turbine. Kaplan turbines are widely used in storage schemes and Run-of-river schemes.



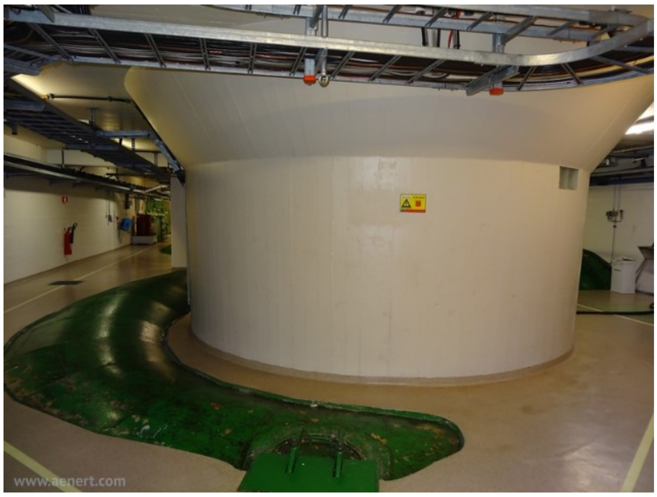


Fig. 9-10. Left - Water turbine application chart (Sources: Wikimedia). Right - The entrance to the Francis turbine through a spiral pipe

Pelton turbines are suitable for high pressures up to 1500 meters and low flows. Externally, the Pelton turbines resemble a water wheel with double-cavity shells at its edges. This design allows for the maximum kinetic energy of the high-speed water jet to be captured, which is directed between the paddles and redistributed between them, ensuring rotation of the turbine.

Fig. 11-12. Left - Francis turbine, Finland. Right - Pelton turbine, Norway

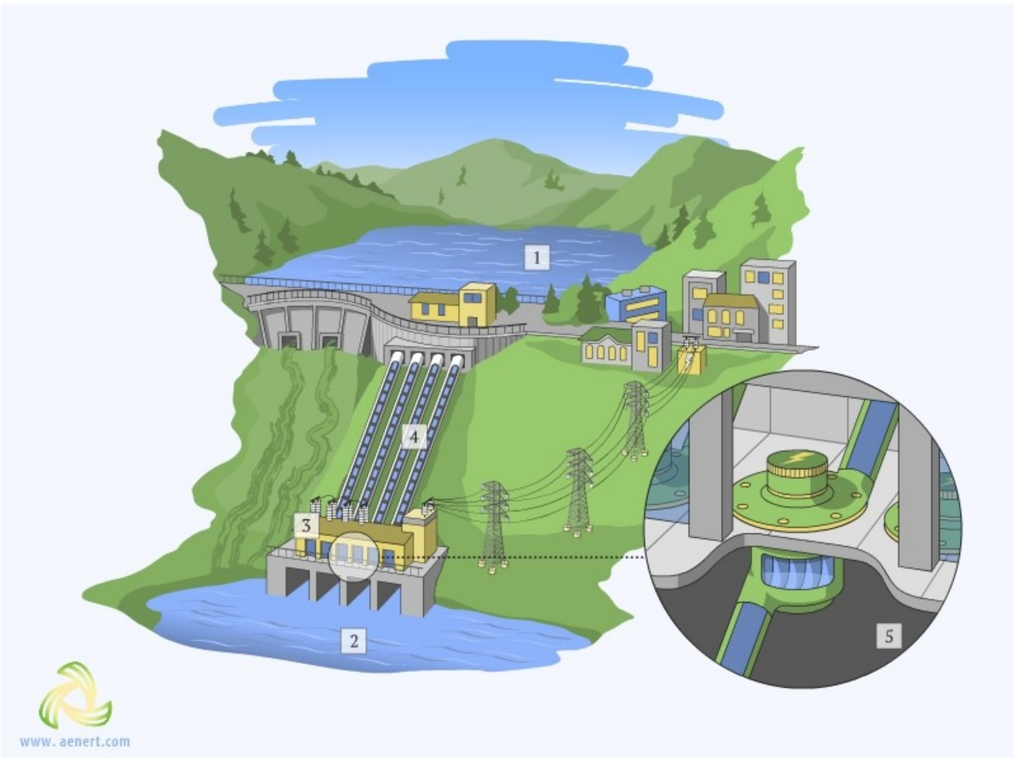
Other types of hydraulic turbines, for example, a Turgo turbine or a Cross-flow turbine have significantly narrower operating ranges of head and flow, which limits their use.

The natural characteristics of hydropower in each particular location, as well as the intended purpose of the hydropower plant, determine both the choice of suitable turbine and the design of hydro facilities and generation order. Effective operation of Run-of-river schemes that do not have additional reserves in the form of reservoirs is only feasible if the river flow has a constant, or at least predictable, head and flow, which is not always possible. A more reliable system is one with storage schemes, which can be used to maintain a constant water flow during periods of suboptimal flow, for example, during seasonal hydrological deviations.

Fig. 13-14. Left - Altenwörth power plant as part of a cascade system on the Danube, 328 MW, Austria; Right - Riga's Hydroelectric Power Plant on Daugava River, 402MW and Riga Reservoir, Latvia

Pumped storage has a fundamentally different purpose and other design features. It is intended for storing water energy in reservoirs located above the hydro turbine unit, for its subsequent deployment for smoothing peak loads or extracting additional economic benefits from the difference in electricity prices at different times of day. Usually at night, when total energy consumption falls and electricity prices decline, the upper reservoir is filled with water from the lower reservoir or directly from the riverbed, Fig. 15. According to [5], the efficiency of such a scheme is between 70%-85%; therefore, such storages are not energy producers, but allow for energy to be saved at large volumes.

Open-loop pumped storage is a system based on an existing hydroelectric power station with an additional upper or lower reservoir. Closed-loops consist of two independent tanks, which are alternately filled with water, depending on the cycle of generation or available capacity of the upper storage.



1. Upper reservoir
2. Lower reservoir
3. Penstock
4. Mashinen hall
5.Turbine/Generator

Fig. 15. Pumped storage scheme

The general operation of pump storage is shown in Fig. 15. It can be illustrated by using the example of a particular station. Located near Malaga, the Tajo de la Encantada pumped storage Power Plant, built in 1977, is an open-loop system and is part of several hydraulic structures located close to each other. The upper reservoir is located at an altitude of 340 meters and is connected to the lower reservoir by a special pipe through which water periodically circulates between them (Figure 16-17). The turbine room has turbines with a diameter of more than 3 meters and a total capacity of 420 MW and is located in the lower tank. The turbine rotation speed is 500 rpm. Such constructions can provide 1 GWh of stored energy, which is sufficient to compensate for the daily peak overload in Malaga and its surrounding area.

Fig. 16-17. Tajo de la Encantada pumped storage Power Plant (El Chorro), 420 MW, Spain. Left – Power Plant; Right - upper reservoir, 340 m

Pumped storage plants today are the main, and essentially only option, for storing energy on a large scale, excluding fossil fuels. The life cycle of such stations can be several decades. China, Japan and the United States are the undisputed leaders in the use of pumped storage technology.

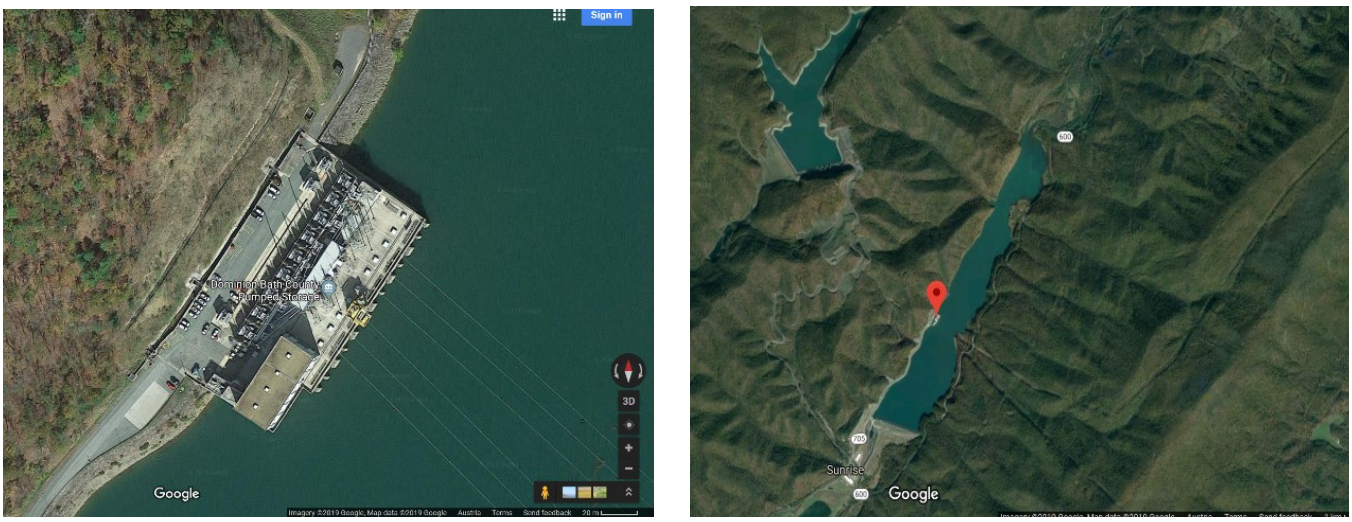


Fig. 18-19. One of the world's largest Pumped Storage Bath County, Virginia, USA, 2.9 GW. Left - top and bottom tanks. Right - the power station
Photos: www.google.com/maps

More information on pumped storage plants can be found in the following sources [44-52].

In operational terms, medium hydropower plants differ little from large ones, beyond differences in scale and corresponding features. A separate group is formed by so-called small hydropower plants, which often include facilities with an installed capacity of less than 10 KW, although different countries may use an alternative gradation from that mentioned above.

Fig. 20-21. Examples of medium and small hydropower plants. Left - Medium power plant Älvkarleby, 12,5 MW, Sweden. Right - Small hydropower plant - Central Pampaneria, Granada, Spain, 12 MW

Small hydropower plants have been most widely utilized in China, where more than 80% of the total global capacity of such power plants have been installed. In the overwhelming majority of cases these power plants operate on Run-of-river schemes without significant reservoirs. Small hydropower plants are often used in isolated or inaccessible areas in the absence of a centralized power grid. In addition, they require fewer environmental approvals before construction, since they have a significantly lower impact on the environment, primarily due to the limited use of reservoirs.

Advantages and disadvantages

One of the main advantages of hydropower is the renewability of hydro resources. Melting snow, heavy rain, and groundwater sources provide annual replenishment of water resources. However, climate change, as well as the consequences of human influence on the natural landscape, has a negative impact on the planet's water balance, especially in certain regions. An example of which can be seen in the case of the Aral Sea in Central Asia (a lake, which once ranked fourth in the world in terms of size), which, due to irrigation diversion projects from the main rivers feeding this lake, has diminished almost tenfold over several decades. Another example of a general negative impact can be found in a change in the usual characteristics of river flows and even in the river beds. For example, forecasts of increasing seasonal fluctuations in the river regime of the Ganges River in India, with several hundred million people living in the basin, are of great concern. Thus, the renewal of water resources is increasingly dependent on objective and subjective factors and requires constant monitoring and adequate response.

Other major advantages of hydropower engineering are the low cost of electricity generation and the low cost of storing a large quantity of energy in reservoirs.

The price parameters for both the construction of hydropower facilities and power generation, have been studied in detail in [1, 53-57]. In [54], the capital cost for the construction of a hydropower plant was calculated from 500$/kW to 4500$/kW. Tunnel structures and reservoirs are the most capital-intensive components, amounting to 14% and 26% of the total costs respectively. The hydropower plant itself and the equipment required totals around 30%, with engineering support accounting for 7% of total costs. Compared to other energy facilities, hydropower facilities are not the most expensive, but remain significantly higher in cost than some conventional power plants, for example, pulverized coal-fired or, most importantly, onshore wind stations.

Technology	Total overnight cost (2018, $/kW)
Conventional gas/oil combined cycle	999
Advanced combined cycle	794
Conventional combustion turbine	1,126
Advanced nuclear	6,034
Biomass	3,900
Geothermal	2,787
MSW - landfill gas	8,895
Conventional hydropower	2,948
Wind	1,624
Wind offshore	6,542
Solar PV – tracking	1,969
Solar PV – fixed	1,783

Table 1. Overnight cost of electricity-generating technologies ($/KW) [53]

While the low cost of coal stations is counteracted by their negative environmental impact, the same is not true of onshore wind energy. However, hydropower retains advantages over wind in that it has a very high capacity factor that can exceed 90%, which for now is unattainable for wind power.

According to research [54], hydropower has on average an extremely low cost of electricity production, which in 2017 was about $ 0.05 / kWh, representing a growth of about $ 0.01 / kWh since 2010. For comparison, during this period, the average electricity prices for various renewable energy technologies changed as follows: biomass - $ 0.07-0.07 / kWh; photovoltaics - $ 0.36 - 0.10 / kWh; onshore wind power -$ 0.08-0.06 / kWh; offshore wind power -$ 0.17 - 0.14 / kWh. Also during this period, the total installation cost of new stations was calculated at approximately 750 to 4500 $ / kW with an average price of 1780 $ / kW in 2016. The most expensive construction of new hydropower stations took place in Europe and North America. The cost of a hydropower plant is determined (in addition to the average cost of construction and equipment) by the hydrogeological features of the landscape, the availability of the necessary infrastructure, access to power grids, etc. In addition, the specific cost of small hydropower plants can be significantly higher - up to $ 10,000 / kW [56]. The share of total cost of pumped storage subcomponents [53,55] is as follows: powerhouse - 37%, upper reservoir - 19%, engineering, etc. - 17%, operator's cost - 17%, other - 10%. During a plant's operational period, which can be several decades, the average cost of electricity generation increases remarkably [56].

Another major advantage of hydropower is the flexibility of its operational modes. Electricity generation can be both increased to peak values within minutes (or even seconds), or reduced in case of oversupply. Such flexibility is not available to either traditional fossil-fuel power plants or modern renewable energy plants. This can be seen in wind and photovoltaic stations, the loads of which rely on favorable weather conditions, i.e. sufficient wind speed and minimal solar activity, respectively.

Among the main disadvantages of hydropower is the frequently encountered discrepancy between the electricity demand in specific areas of the country and the availability of necessary resources, which may be located considerable distances from the main consumers. In this case, the delivery of electricity requires additional expensive infrastructure in the form of power lines and intermediate substations. In addition, the transportation of electricity over long distances generates serious energy losses. Unfortunately, there are no comprehensive solutions to this problem, beyond finding reasonable compromises between cheap energy in a remote region or more expensive energy in a less distant region.

The construction of large power plants requires large areas of land, which are often being used, for example, for agricultural purposes or human habitation. This leads to higher investment costs of the projects due to the need to compensate for loss of land, and relocation, and can also lead to more serious social conflicts.

Even more complex assessments arise when considering the issue of Environmental footprint. A detailed review of this problem is considered in [8]. There are several groups of important issues - safety; water use and water quality impacts; impacts on migratory species and biodiversity; reservoir sedimentation and debris; and lifecycle greenhouse gas emissions. This document notes that the influence of hydroelectric power plants on water quality is largely determined by existing conditions - the quality of the input stream, the terrain, the type of station, etc. Nevertheless, there are special methods for calculating the evaporation of water and its distribution for specific purposes. It is also possible to improve the quality of operation with new turbine designs. The restriction dams place on the free migration of fish is frequently mentioned among other drawbacks of hydroelectric power plants, this is especially true in the case of old power plants. However, modern technologies of laying additional bypass channels and changes in the riverbed, as well as the use of special turbines such as an Alden turbine, ensure the survival of more than 95% of fish. Careful planning of the construction and operation of stations, including flow management programs, significantly reduces the negative impact on biological species. The authors in [8] also describe the problems of water transfer of various sediments, such as sand, gravel, silt and clay particles, which can affect both the reservoir capacity and the environment. They also suggest solutions to these problems, or various ways to at least reduce the negative environmental impact.

Issues of safety of hydraulic structures have always been the focus of attention during their construction or operation. Errors in the design of the station or in its management can cause large-scale destruction, environmental disasters, and human fatalities. Source [58] provides a list of incidents at major hydropower stations in recent decades. For example, in February 2017, there was a breakthrough of the dam and destruction of the main spillway at the Oroville Dam in the USA due to heavy rainfall and structural vulnerability. Fortunately, there were no casualties and the surrounding area did not need to be evacuated. However, the cost of repairing the station exceeded $ 1 billion [59]. In February 2019; there was a major accident at the Hidroituango dam, operated by EPM, on the Cauca River in Colombia, the consequences of which are still to be evaluated [60]. The $ 4 billion project contained engineering failures in the construction of the dam which in conjunction with heavy rain and landslides, led to an uncontrolled spillway through drainage tunnels and the dam itself, resulting in the flooding of large areas in the vicinity, and catastrophic shallowing of the second-largest river in Colombia. Tens of thousands of people were evacuated, thousands of fish died, and there were problems with the irrigation of agricultural areas, etc.

These examples indicate that the influence of natural phenomena are not always adequately taken into account when designing and operating hydraulic structures. This can lead to serious negative consequences and adds a layer of complication in any assessment of advantages and disadvantages of the technology. Perhaps the more frequently occurring natural anomalies, driven by climate change, require the reevaluation of power plant design, construction and operation .

Hydro energy statistics

According to statistics from [61], the total installed capacity of hydropower in the world was 1,114 GW, or about 51% of all installed renewable energy capacities. IRENA in [62] provides higher figures - 1,275.5 GW for 2017, compared to 962 GW in 2008. Over the past 10 years, total hydropower capacity has increased by more than 32% [62]. It was noted above (Fig. 1-2) that in the total volume of electrical energy generation the share of hydropower is 17%, and in the consumption of primary energy its share is around 7%. The total hydroelectric power consumption in 2017 was 918.6 Mtoe, which is more than one and a half times larger than that of nuclear power, more than three times less than the consumption of coal and natural gas and more than 4 times less than oil consumption [7].

Figures 22-23 show the share of the total hydropower capacity for the top 10 countries of the world, as well as the share hydropower plants by type.

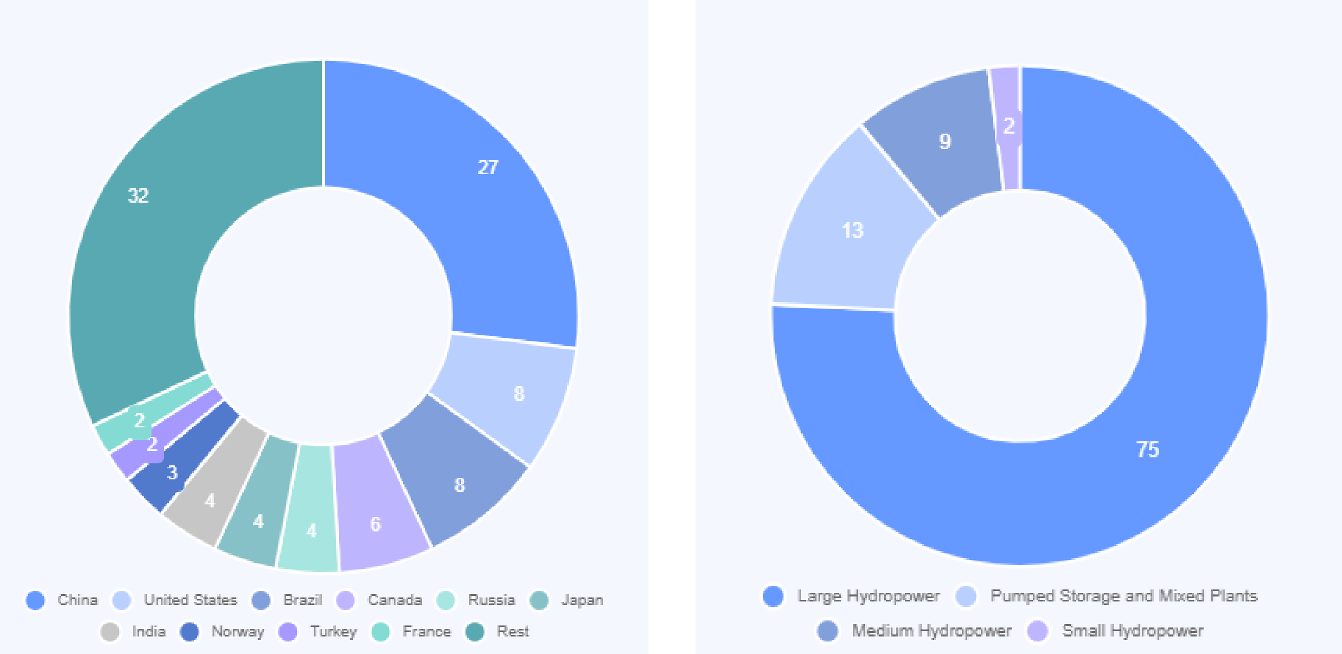


Fig. 22 - 23. Left - Top-10 Countries by Hydropower Capacity in the World, 2018. To the right - Share of Hydropower Energy Capacity by Type in the World, 2016. (% of total)
Sources: Based on Data from RENA (2019), Renewable capacity statistics 2019, International Renewable Energy Agency (IRENA), Abu Dhabi; IRENA (2017), Renewable energy statistics 2017, International Renewable Energy Agency (IRENA), Abu Dhabi

China is the absolute leader in installed hydropower capacity, accounting for about 28% of the world total. The ten largest countries by this indicator are completed by the USA, Brazil, Canada, Russia, India, Japan, Norway, Turkey and France. China is also the absolute leader in terms of Small Hydro Power Capacity, accounting for 83% of the global installed capacity [62]. The share of large hydropower plants amounts to 75%, with the total capacity of pumped storage plants having a share of 13%, medium-sized hydroelectric power stations about 9% and small ones 2% [62].

For many countries, both large and small, hydropower is the main source of electricity. For example, in Norway about 97% of electricity is produced from hydropower, over 66% in Brazil, 59% in Canada, over 40% in Sweden, and about 20% in China. Fig. 24.

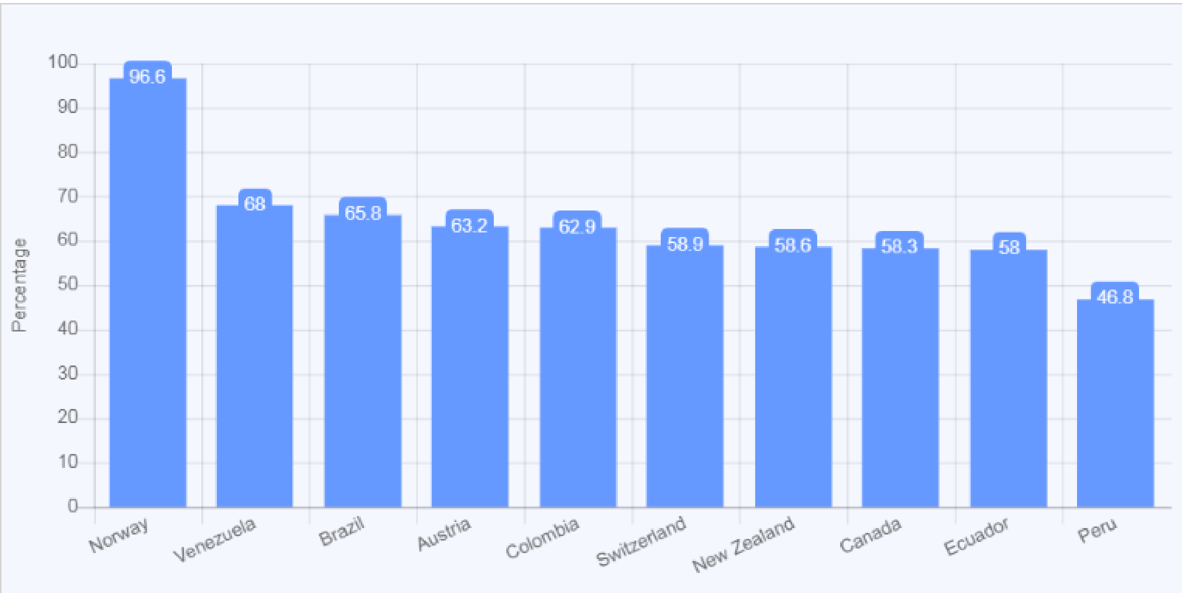


Fig. 24. Top 10 global countries rated by Hydropower generation to total production, 2016 (for countries with an annual electricity production of at least 10 TWh). In 2016 hydro power plants in these countries generated approximately 64.4% of total electricity generation
Sources: Based on Data from IRENA (2018), Renewable Energy Statistics 2018, International Renewable Energy Agency (IRENA), Abu Dhabi; BP Statistical Review of World Energy June 2018

Data on electricity generation by leading producers is presented below on the main hydropower plants maps. The dynamics of the cumulative growth of capacity of pumped storage plants in the world in recent years, as well as their annual growth over this period are presented in Fig. 25.

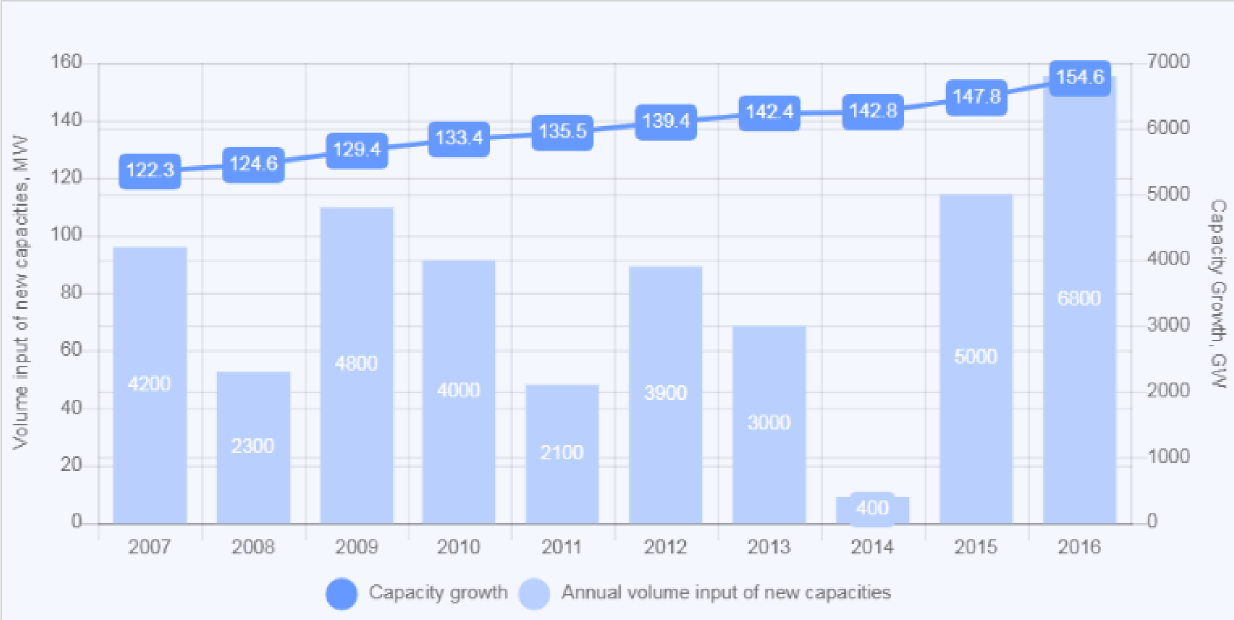
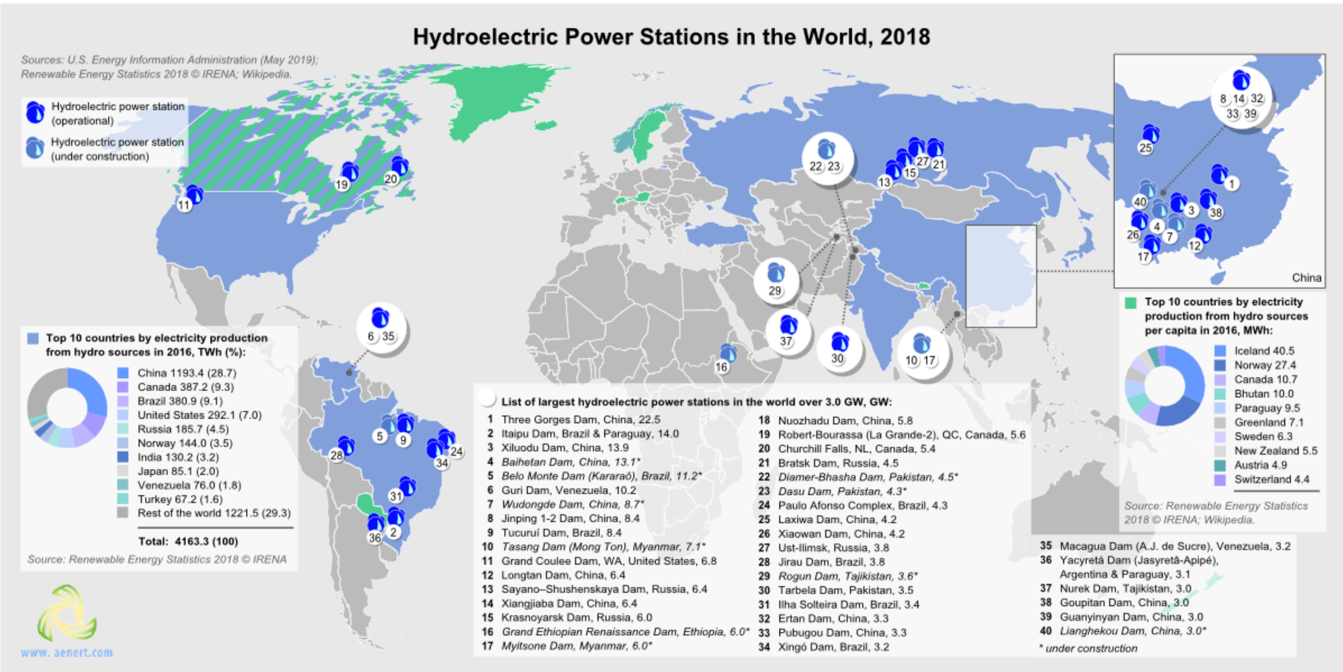


Fig. 25. Rated power of pure pumped hydro storage capacities growth & Annual Volume Input of new Capacities in 2007-2016
Source: Based on Data from U.S. Energy Information Administration (May 2019)

Hydro power plants

In 2016, 24,930.2 TWh of electricity was produced worldwide [7], of which just over 4,000 TWh was produced at hydropower stations [62]. In China, hydropower generated over 1193.2 TWh, the highest in the world, followed by Canada with 387.2 TWh, and Brazil with 380.9 TWh [62]. The top 10 countries in terms of electricity production, as well as the location and capacity of the top 40 largest power plants with capacities over 3.0 GW can be seen in Fig. 26.

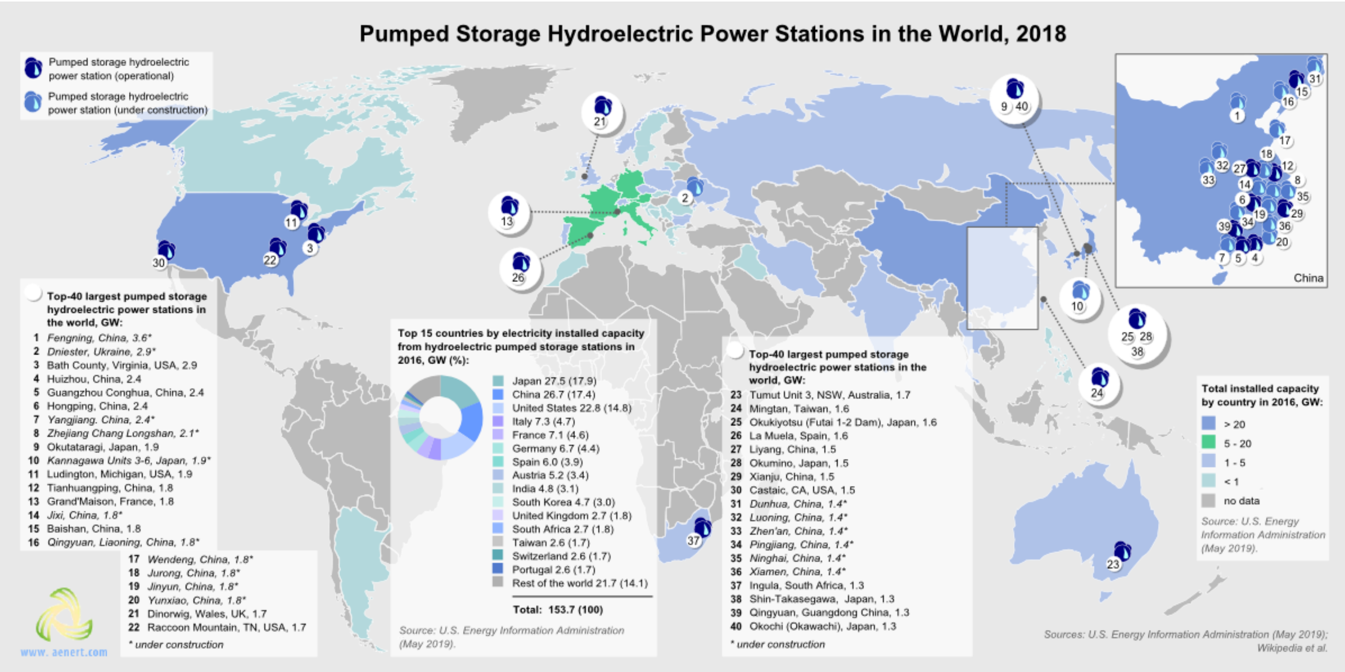


[Hydroelectric power stations in the world 2018](#) *[755 KB]*
Fig. 26 The largest hydropower plants in the world.

Also shown are the top 10 countries in the world in terms of electricity production per capita. The undisputed leader here is Iceland, where more than 40 MWh of electricity is generated per resident followed by Canada, which produced 10.7 MWh per capita in 2016. Also on the list are Norway, Bhutan, Paraguay, Sweden, Austria, Switzerland and New Zealand.

As mentioned above, the Three Gorges Dam in China and the Itaipu Dam in Brazil-Paraguay are the largest hydropower plants on the planet with capacities of 22.5 and 14 GW respectively. Another four Chinese hydropower plants and two from Brazil (including those under construction) are among the 10 largest in the world. To this group can be added the Guri Dam in Venezuela (10.2 GW) and the Tasang Dam (7.1 GW) in Myanmar. In total, China operates or is building 15 large power plants with capacities over 3.0 GW. In Brazil, there are 7 such hydroelectric power plants, in Russia - four, and in Pakistan - three.

The most powerful pumped storage stations in the world are shown in Fig. 27. Three countries are clear leaders in terms of installed capacity of pumped storage plants - Japan with 27.5 GW (17.9% of the world total capacity in 2016), China, with 26.7 GW (17.4%) and the USA - 22.8 GW (14.8%). Together, their share is more than 50% of the total installed capacity.



[Pumped storage hydroelectric power stations in the world 2018](#) [724 kB]
Fig. 27. The world's largest pumped storage power plants

A large number of pumped storage stations are located in Europe. Italy (7.3 GW), France (7.1 GW), Germany (6.7 GW), Spain (6.0 GW), Austria (5.2 GW), Great Britain (2.7 GW), Switzerland (2.6 GW) are among the top 15 countries globally in installed capacity. The largest of the existing pumped storage plants is Bath County in Virginia, USA with a capacity of 2.9 GW. However, the most powerful pumped storage station among those under construction is located in China - Fengning (3.6 GW). The largest stations in Japan - Okutataragi and Kannagawa - have a power of 1.9 GW each.

More information about hydroelectric power plants of various types in the world can be found in the following sources - [42,45,63].

Major companies

Given the scale of hydropower in the world, there are a huge number of different companies operating hydropower plants, supplying turbines, electrical equipment, software, and providing other services. Among them, the largest operators include China Yangtze Power Company (CYPC), Hydro-Québec, Ontario Power Generation (Canada), Eletrobras (Brazil), EDF (Électricité de France), Manitoba Hydro, Duke Energy, Southern California Edison Company (USA), RusHydro (Russia), Tokyo Electric Power Company (TEPCO), Verbund (Austria), RWE AG (Germany) among many others.

China Yangtze Power Company (CYPC) is one of the largest hydropower companies in the world with 82 plants with a total installed capacity of 45,495 GW [64]. Brazil's largest energy company, Eletrobras (total installed capacity - 48.1GW), generated 182.1 TWh of electricity in 2017, of which more than 90% was generated through 48 hydropower plants [65]. Hydro-Québec, one of the largest in Canada, operates 36.4 GW of hydroelectric power [66]. The total installed capacity of the plants operated by the Russian RusHydro is 39.4 GW, and the volume of generated electricity was 144.2 TWh in 2018. The company operates the largest plant in Russia, the Sayano – Shushenskaya Dam, with a capacity of 6.4 GW and the Krasnoyarsk Dam, with a capacity of 6.0 GW [67].

Fig. 28-29. Left - Hoover Dam on the Colorado River (USA), 2,080 MW, Head 180 m (1931).
Right - Írafossstod Power Station (Iceland), 48 MW

The most important technological element of any power plant is the hydro turbine. Among the major suppliers are the following companies - Andritz AG (Austria), Caterpillar, Inc., General Electric Company, GE Power & Water, American Hydro (USA), Dongfang Electric Corporation Limited (China), Toshiba Corporation, Mitsubishi Heavy Industries, Ltd. (Japan), Siemens (Germany).

One of the oldest suppliers of hydraulic turbines is the Austrian Andritz Hydro [68], which has more than 175 years of experience. The company is represented in 280 branches in more than 40 countries. The company has installed more than 430 GW capacities in various countries in Europe, North and South America, Africa and Asia. Andritz Hydro supplies most standard types of turbines, as well as special-purpose turbines (pumped turbines, turbines for tidal currents, etc). The company's research activities are aimed at increasing the flexibility and reliability of power plant equipment, and the comprehensive optimization of hydraulic, mechanical and electrical characteristics [68]. Among the company’s products is the innovative Hydromatrix type turbine, which combines the advantages of advanced technologies with low installation costs and can be easily integrated into existing dam structures [68]. These turbines, as evidenced by more than 15 years of practice, can operate in areas with low pressure up to 19 m. This type of turbine is mainly in demand in Europe.

The dynamics of the value of shares of some public hydropower companies are presented in Fig. 30. The starting point is 2009 - the first year after the financial crisis, when most stock market indicators experienced a serious fall. Data on stock values are given against the background of the value of the generalized Nasdaq Composite Index.

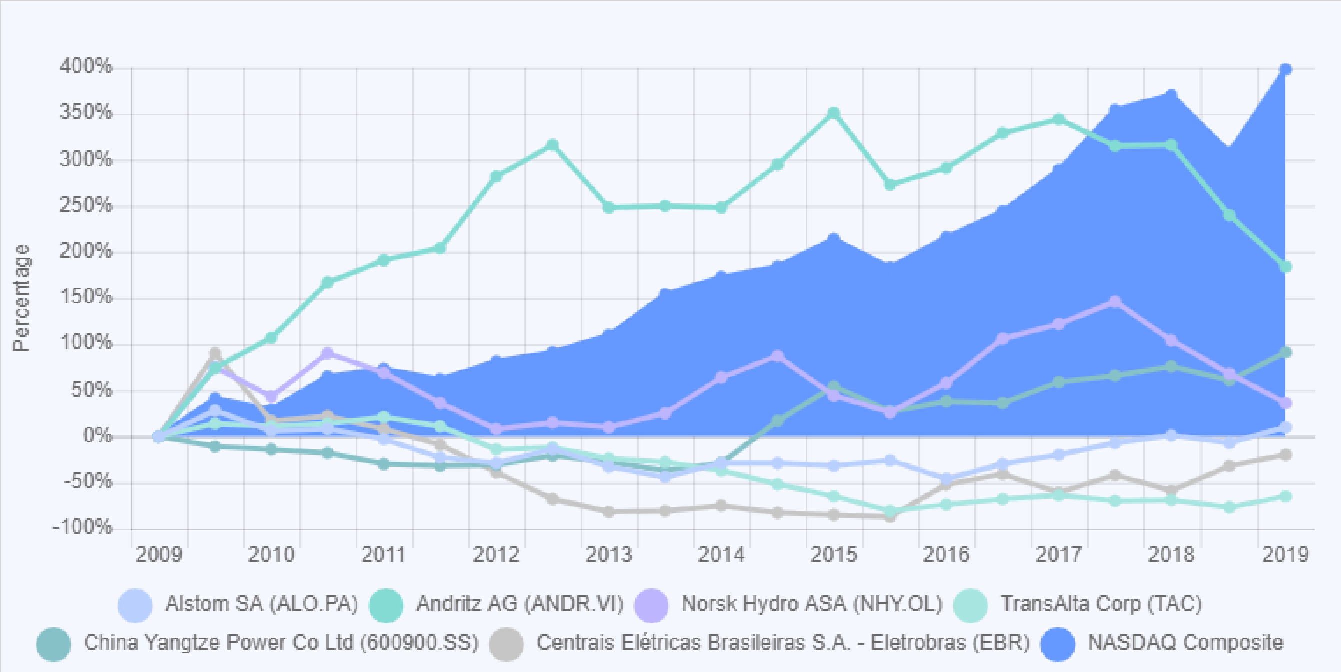


Fig. 30. The dynamic of the stock price of hydro energy companies. Data in 2009 given as zero point
Source: Yahoo Finance

Most of the companies represented show a positive trend by the beginning of 2019, particularly Andritz AG. Other companies show a more modest upward trends or are in a negative zone compared to the starting year.

Generalized and more detailed information on the activities of various hydropower companies can also be found here - Advanced Energy Technologies or on the following websites [42,44,69]

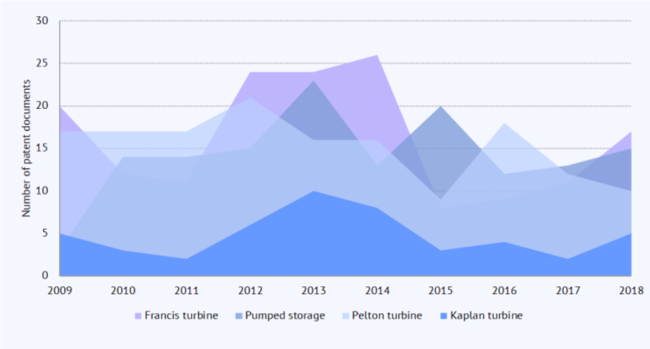
Research and innovations

Hydropower, despite being one of the oldest players in the energy market, is influenced by innovative development. New increased requirements for hydraulic structures, primarily from the point of view of technical and environmental safety, and desire for reducing project costs and increasing energy efficiency, stimulate in-depth research. This help to detect into the fundamental mechanisms for converting water flow energy into electrical energy, the impact of energy reservoirs and hydraulic structures on the surrounding flora and fauna, and nature corrosion resistance of materials and many other scientific and technological applications.

High quality statistics on the latest innovative proposals can be obtained by analyzing the patent applications of the World Intellectual Property Organization, WIPO. A brief overview of patent applications published in WIPO from 2009 to 2018 on topics related to hydropower is shown below. The following search code was used to search for applications:

OF:WO AND DP:[2009 TO 2018] AND ((FP:("Pumped storage") OR CL:("Pumped storage") OR (IC:F03B13/06 AND (FP:pump* OR CL:pump*))) OR (FP:(Kaplan AND (turbine* OR hydro OR hydroelectric)) OR CL:(Kaplan AND (turbine* OR hydro OR hydroelectric)) OR IC:F03B3/06) OR (FP:(Pelton AND (turbine* OR hydro OR hydroelectric)) OR CL:(Pelton AND (turbine* OR hydro OR hydroelectric)) OR IC:F03B1) OR (FP:(Francis AND (turbine* OR hydro OR hydroelectric)) OR CL:(Francis AND (turbine* OR hydro OR hydroelectric)) OR IC:F03B3/02) OR (FP:(Hydro NEAR power) OR FP:(hydroelectric NEAR power) OR FP:(Hydro NEAR energy) OR FP:(hydroelectric NEAR energy) OR FP:(hydro NEAR turbine) OR FP:(hydroelectric NEAR turbine) OR CL:(Hydro NEAR power) OR CL:(hydroelectric NEAR power) OR CL:(Hydro NEAR energy) OR CL:(hydroelectric NEAR energy) OR CL:(hydro NEAR turbine) OR CL:(hydroelectric NEAR turbine))).

A total of 1052 documents were identified. The distribution of patent applications by year is presented below in Fig. 31. The distribution of the number of patent documents related to the three main types of hydraulic turbines, as well as those associated with Pumped storage, can be seen in Fig. 32.



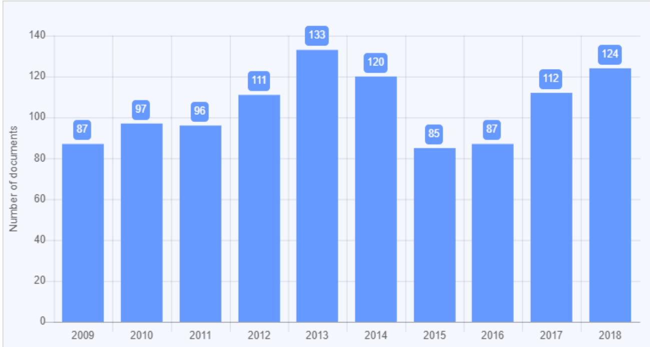
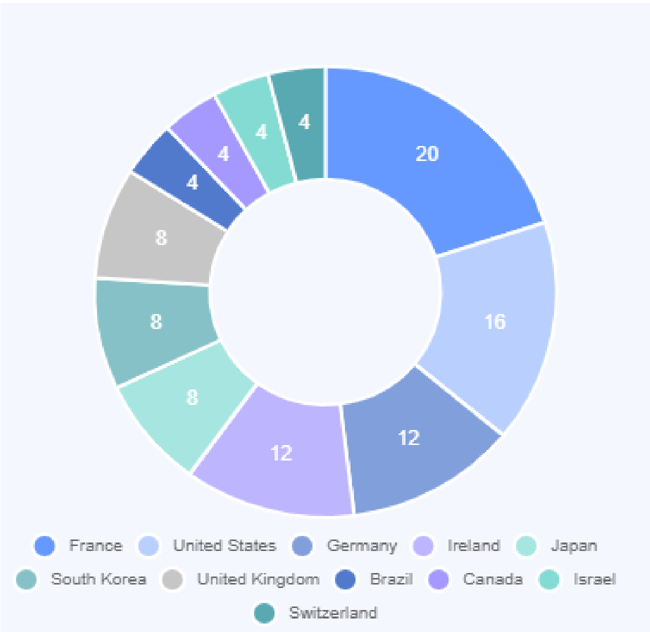


Fig. 31-32. Left - Distribution of the number of WIPO patent documents related to the Kaplan, Pelton and Frankis hydraulic turbines, as well as to Pumped storage for 2009-2018. To the right - Distribution of identified WIPO patent applications on topics related to hydropower for the period from 2009 to 2018
Source: Based on WIPO data

As follows from the diagrams presented, there was an equal amount of focus on the improvement of the Pelton and Francis turbines, with less focus on Kaplan turbines. Patent activity reached its peak in 2013–2014, then, after a two-year hiatus, began to show significant growth. This trend was mirrored in other patent offices and technologies. The following keywords were most commonly used in patent applications: Power (34.9%), System (25.2%), Turbine (21.5%), Energy (19.5%), Method (21.1%), Hydroelectric (19.5%), Generation (13.6%), Plant (13.1%), Device (12.4%), and Water (9.9%).

Figures 33-34 show the share of countries whose residents are among the top 25 applicants (Fig. 33) and the ratio of the top 10 most frequently mentioned classes of the International Patent Classification - IPC.

France (20%) is mentioned more often than other countries, among the 25 top applicants by number of registered documents, followed by the USA (16%), Germany (12%) and Ireland (12%).



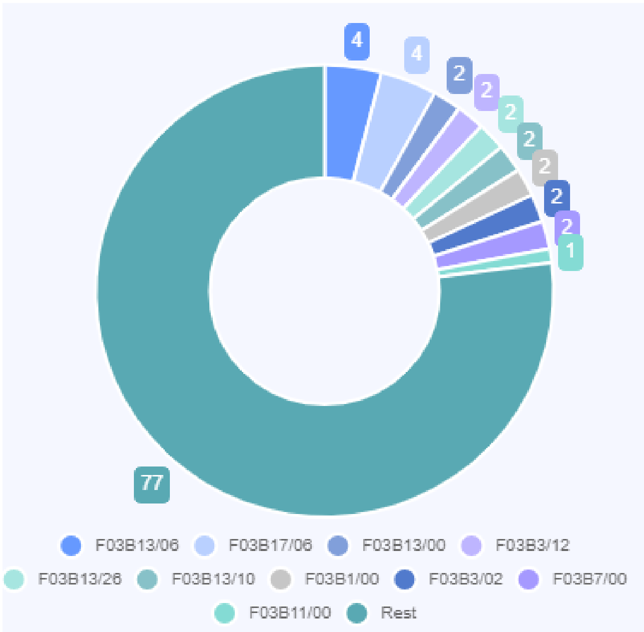


Fig.33-34. On the left - the shared distribution of countries whose residents are among the top 25 applicants. On the right is the proportion of the top 10 most frequently mentioned classes of the international patent classification
Source: Based on WIPO data

Most commonly, in 4% of cases, the inventors classified their inventions under the two following classes of the IPC - F03B13/06 (Stations or aggregates of water-storage type (turbines characterized by having the means to function alternatively as pumps)) and F03B17/06 (using liquid flow, eg. of swinging-flaptype).

The following classes were mentioned to a lesser extent (2% in each case): F03B13/00 (Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus (if the apparatus aspects are predominant, see the relevant places for such apparatus, e.g. H02K0007180000), F03B3/12 (Blades; Blade -carrying rotors), F03B13/26 (using tidal energy), F03B13/10 (Submerged units incorporating electric generators or motors), F03B1/00 (Engines of impulse type, i.e. turbines with jets of high-velocity liquid impinging on bladed or like rotors, e.g. Pelton wheels; Parts or details peculiar thereto), F03B3/02 (with radial flow at high-pressure side and axial flow at low-pressure side of rotors, e.g. Francis turbines), F03B7/00 (Water wheels).

The top 10 applicants and their share in the total array of patent selection, by number of documents are presented in Table 2.

Applicant	Country	No. of applications	Share of applications, %
Voith Patent Gmbh	Germany	41	3.90
Korea Hydro & Nuclear Power Co., Ltd	S. Korea	36	3.42
Openhydro Ip Limited	Ireland	27	2.57
General Electric Company	USA	24	2.28
Alstom Renewable Technologies	France	14	1.33
Dunne, Paul	Ireland	14	1.33
Alstom Hydro France	France	13	1.24
Ives, James	Ireland	13	1.24
Safran Aircraft Engines	France	12	1.14
United Technologies Corporation	USA	9	0.86%

Table. 2. Top 10 applicants in the collection of WIPO patent applications in the field of hydro energy technologies, 2009-2018. (A total of 1,052 documents submitted by 1,414 applicants were processed)
Source: Based on WIPO data

Among the top 10 applicants the representatives of Ireland (a total of 44 documents) and France (39 documents) are most common. The rest of the countries include the United States, Germany and South Korea, but produced significantly fewer documents. Nevertheless, the only representative of Germany on this list - Voith Patent Gmbh became the leader in the number of registered documents with a share in the intellectual property market of 3.9%.

Research programs in the field of hydropower cover several major areas. One of these areas concerns increasing the efficiency of turbines, providing greater flexibility in the operation of hydraulic units, increasing the time between turnarounds and reducing equipment downtime. Another important area of research is related to the problems of materials science in relation to aqueous elements and various hydraulic phenomena such as corrosion, destruction of turbines due to cavitation processes, and wear, including abrasive content of sand and other solid particles in water streams, and fatigue failure of metals from alternating loads. Improving the quality and optimizing the construction of hydraulic structures is the most significant way to reduce the cost of hydropower projects, since construction, as mentioned above, constitutes the main share of total costs (from 40 to 70% or more). Therefore, the development of new technologies in the construction of hydropower is also the subject of scientific research and organizational improvements.

Research in the field of creating new concepts of pumped storage plants offers interesting prospects. For example, the concept of an energy island by the Dutch company Kema, consisting of an annular dam in the sea with an inland lake, whose level is 32–40 meters below sea-level[8], gained much attention. The potential for storing energy in such a facility could be up to 1500 MW. Certainly, the development of such technology, which does not require special landscape characteristics, can significantly expand the geography of distribution of pumped storage technologies.

The statement by the Australian National University (ANU) regarding the results of a global audit of 530,000 potential sites for the construction of pumped storage stations [70] was even more revolutionary. According to the authors of the project, the development of only a small fraction of these sites would be sufficient to provide 100% of the world's continuous energy supply. If the results of the study prove to be correct, this may lead to a global rethinking of the energy strategies of many states and contribute to the accelerated development of wind and solar energy, the main drawback of which is their intermittent operation.

Another potentially significant water energy storage technology has been proposed in Germany. This is a special design of wind turbine in conjunction with the pumping unit of Max Bögl Wind AG, which has received patent approval [71, 72]. The company specializes in the installation of wind turbine hybrid towers with a height of 130 meters, supported by water batteries with a pumping power plant, the water battery acting as a short-term storage and ensures network stability.

More detailed information on the latest scientific and technological achievements in the field of hydropower can be found in specialist publications [73, 74]. A list of many research organizations in the field of hydropower, publishing their research papers in the leading specialist magazines can be found at Advanced Energy Technologies in the Research Organizations section.

Trend of development

Estimates of hydropower development up to 2050, proposed by various energy agencies and government organizations, differ significantly from each other, because they depend on the varying development scenarios and the degree to which global factors of economic and technological development are taken into account. For example, according to the BLUE Map scenario in the Energy Technology Perspectives 2010 [1], whose main goal is to reduce CO_2 emissions in the energy sector by 50% by 2050, it is assumed that the share of hydropower will decrease to 14.1% and amount to slightly less than 5,749 TWh.

In the short-term development forecast up to 2023, developed by the International Energy Agency (IEA), it is indicated that despite the slowdown in the growth of new hydropower capacity, the total will increase by 2023 to 125 GW, and 40% of this increase will be provided by China [75].

In the IEA's long-term deployment model aimed at reducing the average temperature by 2°C (ETP 2DS) 2012 [8], the global installed hydropower capacity is estimated to be 1,947 GW by 2050, i.e., almost doubling, and hydropower generation will reach about 7,100 TWh. In the baseline scenario for 6°C (6DS), it is assumed that the growth in capacity will be limited to 5,700 TWh, and the share of hydropower in the total generation will decrease by approximately 12%.

U.S. The Energy Information Administration has evaluated the production of electricity from renewable sources, including hydropower, until 2040 [76].

The forecast data is summarized in Table 3.

Countries	2015	2040	Change 2040-2015, %	Change in the World-2015, %	Change in the World-2040, %
World	3850	5678	47.48	100	100
China	1042	1645	57.9	27.06	29
India	128	201	57.03	3.32	3.54
Japan	81	80	-0.01	2.1	1.41
OECD Europe	563	830	47.42	14.62	14.62

Tabl. 3. Net electricity generation from hydropower power, billion kilowatt hours
Source: Based on Data from International Energy Outlook 2017, U.S. Energy Information Administration (September, 2017)

The total growth of electricity generation via hydropower, according to [77], may reach approximately 1,800 TWh by 2040. The greatest contribution to this process is expected to be made by China, whose share of the world's hydropower market by 2040 will be 29%.

In [77], according to one scenario, the share of hydropower in the total amount of electricity generation by renewable sources in the USA will fall to 18% from 20% in 2018, and the main role will be played by solar energy (48%) and wind energy (25%).

Various options for the development of renewable energy for the period up to 2050 are considered in [78] (Reference Case, REmap Case). In the latter case, compared to the reference case, the issues of the impact of energy on socio-economic development are taken into account. For example, the authors take into account such factors as an increase in welfare by 15% by 2050, GDP by 1% and employment by 0.1%. According to the REmap Case option, by 2050 the share of renewable energy in electricity generation will increase from 24% to 85% and the share of hydropower in total electricity generation will decrease from 16% to 12%. At the same time, the total generation volume in 2050 will reach 41,508 GWh/year. It is also assumed that hydropower capacity will increase from 1,248 GW, with 155 GW pumped storage stations, to 1,828 GW with 325 GW of pumped storage.

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