Hydropower

Technology Brief

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

Insights for Policy Makers

Hydropower is a mature and fairly simple technology: the potential energy of a water source (characterised by its head and mass flow rate) is converted into kinetic energy that spins a turbine driving an electricity generator. The kinetic energy of falling water was used for grinding wheat more than 2000 years ago. Since late 19th century, hydropower has been used to generate electricity. At present, about 160 (of the world's some 200) countries worldwide use hydropower technology for power generation. With a total installed capacity of 1060 GW_e (19.4% of the world's electric capacity in 2011), hydropower generates approximately 3500 TWh per year, equivalent to 15.8% of global electricity generation. Hydropower plants provide at least 50% of the total electricity supply in more than 35 countries. They also provide other key services, such as flood control, irrigation and potable water reservoirs. Hydropower is an extremely flexible electricity generation technology. Hydro reservoirs provide built-in energy storage that enables a quick response to electricity demand fluctuations across the grid, optimisation of electricity production and compensation for loss of power from other sources. Special attention is now paid to pumped hydropower plants as they are at present the most competitive options for large-scale energy storage to be used in combination with variable renewables (e.g. solar and wind power).

Hydropower plants consist of two basic configurations: the first based on dams with reservoirs and the second, run-of-the-river scheme (with no reservoir). The dam scheme can be sub-divided into small dams with night-and-day regulation, large dams with seasonal storage and pumped storage reversible plants for both pumping and electricity generation that are used for energy storage and night-and-day regulation, according to electricity demand. Small-scale hydropower is normally designed to run in-river, an environmentally friendly option since it does not significantly interfere with the river's flow.

The development and construction of hydropower plants requires a long lead time, especially for the dam-with-reservoirs configuration. The investment costs for new hydropower plants, including site preparation and civil engineering work, depend significantly upon the specific site. Investment costs include planning and feasibility assessments, environmental impact analyses and licensing. Recent investment cost figures for large hydropower plants ranged from USD 1050/kW to USD 7650/kW. For small hydro projects, the range varies even more, from USD 1000/kW to USD 10 000/kW. Considering annual operation and maintenance costs, ranging 1%-4% of the investment costs, the typical levelised cost of electricity (LCOE) ranges from USD 20-190/MWh for large hydropower and USD 20-270/MWh for small-scale hydropower. Hydropower production depends upon rainfall in the upstream catchment area. Reserve capacity may be needed to compensate for periods of low rainfall and this may increase the investment cost.

Globally, technical hydropower potential is estimated at around 15 000 TWh. In most developed regions (e.g. Europe), a significant fraction of the economically viable hydropower potential is already being exploited, although about 50% of the technical potential is still untapped. The most untapped region is Africa, where 92% of the total potential has not yet been developed. Large hydropower projects can raise environmental or social concerns because they may heavily affect water availability in large regions, inundate valuable ecosystems and lead to relocation of populations. There are also concerns about greenhouse gas (GHG) emissions from reservoirs, both from the decomposition of organic material initially inundated, and, throughout the lifetime of the scheme, of organic material deposited from further upstream These are related to the public acceptance activities that should be carefully considered by both policy makers and developers. High investment costs and long payback periods are also major characteristics of hydropower development. Other barriers, such as stringent environmental standards for water management, can also hamper hydropower development.

TECHNICAL HIGHLIGHTS

- **Process and Technology Status –** Hydropower is a mature technology that is currently used in about 160 countries to produce cost-effective, low-carbon, renewable electricity. With a total capacity of ca. 1060 GW_e (19.4% of the world's electric capacity in 2011), hydropower generates about 3500 TWh per year, equivalent to 15.8% of 2011 global electricity generation. Hydropower plants provide at least 50% of the total electricity supply in more than 35 countries. They also provide other key services, such as flood control and irrigation. Hydropower plants consist of two basic configurations: the one based on **dams** with reservoirs and the other **run-of-the-river** plants (with no reservoirs). The dam scheme can be sub-divided into **small dams** with night-and-day regulation, **large dams** with seasonal storage and **pumped storage** reversible (either generating and pumping) plants for energy storage and night-and-day regulation, according to electricity demand. Small-scale hydropower is often used for distributed generation applications as an alternative to, or in combination with, diesel generators or other small-scale power plants for rural applications.

- **Performance and Costs –** Hydropower is a cost-effective electricity source. It offers high efficiency and low operating and generation costs, though its upfront investment cost is relatively high. One of the advantages of hydropower is its operational flexibility. The capacity factor of hydropower plants varies between 23%-95%, depending on targets and the service (*i.e.* baseload, peakload) of the specific power plant. The investment costs for large hydropower plants (>10 MW_e) range from USD 1050-7650/kW_e (calculated in 2010 USD) and are very site-sensitive. The investment costs of small (1–10 MW_e) and very small hydropower plants (VSHP) (≤1 MW_e) may range from USD1000-4000/kW_e and USD 3400-10000/kW_e, respectively. Operation and maintenance (O&M) costs of hydropower plants are typically between 1%-4% of annual investment costs. The levelised cost of electricity (LCOE) typically ranges from USD 20-190/MWh for large hydropower plants, from USD 20-100/MWh for small plants and USD 270/MWh or more for very small plants.

- **Potential and Barriers –** The global technical hydropower potential is estimated at around 15000 TWh per year. Half of this total potential is available in Asia and 20% in Latin America. Large untapped technical potential is still available in Africa, Latin America and Asia, while in Europe it is only around half of the total technical potential. However, large hydropower projects can encounter social opposition because of their impact on water availability, ecosystems and the environment, and the need to relocate populations that may be affected by the project. Major hydropower issues include public acceptance, high initial investment costs and long payback periods, long approval and construction cycles, and long lead times to obtain or renew concession rights and grid connections. Environmental protection is also a key issue that deserves consideration. These challenges are likely to limit the implementable hydropower potential.

Process and Technology Status

Hydropower is a mature technology. Since the late 19^{th} century, the kinetic energy of falling water has been used to produce electricity in hydropower plants. Today, hydropower is used in about 160 countries worldwide. With a total installed capacity of 1060 GW_e (19.4% of the world's electric capacity) in 2011, hydropower generated approximately 3500 TWh per year, equivalent to 15.8% of all global electricity generation. Hydropower plants provide at least 50% of the total electricity supply in more than 35 countries.

The world's largest hydropower electricity producer is China, which generated about 700 TWh in 2010, followed by Brazil, Canada and the United States. The hydropower capacity installed in these four countries alone generates half of the world's total hydropower electricity.

Hydropower also provides other key services, such as flood control, irrigation and potable water reservoirs. Hydropower is an extremely flexible electricity generation technology. Hydro reservoirs provide built-in energy storage that enables a quick response to electricity demand fluctuations across the grid, optimisation of electricity production and compensation for power losses from other sources.

Hydropower plants have two basic configurations: **dams with reservoirs** and **run-of-river** plants, with no reservoirs. The dam scheme can be sub-divided into **small dams** with night-and-day regulation, **large dams** with seasonal storage and **pumped storage** reversible plants (for pumping and generation) for energy storage and night-and-day regulation, according to fluctuating electricity demands.

Small-scale hydropower is normally designed to run in-river. This is an environmentally friendlier option because it does not significantly interfere with the river's natural flow. Small-scale hydro is often used for distributed generation applications (similar to diesel generators or other small-scale power plants) to provide electricity to rural populations.

A generic hydropower plant scheme based on a dam and reservoirs is shown in Figure 1. The scheme is quite simple: water released from the reservoir at the inlet dam on higher side that has a potential energy flows through a pipe or tunnel to a turbine. The water's potential energy is converted to kinetic energy and spins the blade of a turbine, which activates a generator to produce electricity. One of the advantages of hydropower is its operational flexibility. In other words, the capacity factor of hydropower varies depending on the specific plant and its services (*i.e.* baseload, peakload) between 23%-95%.

Figure 1: Generic scheme of a hydropower plant based on a dam (Bøckman et al., 2006)

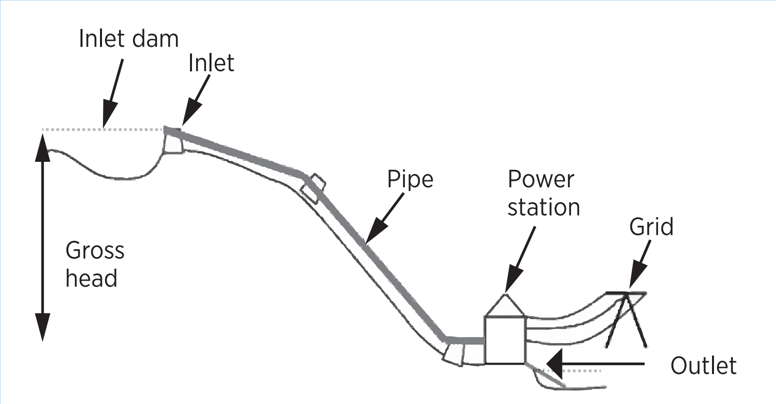
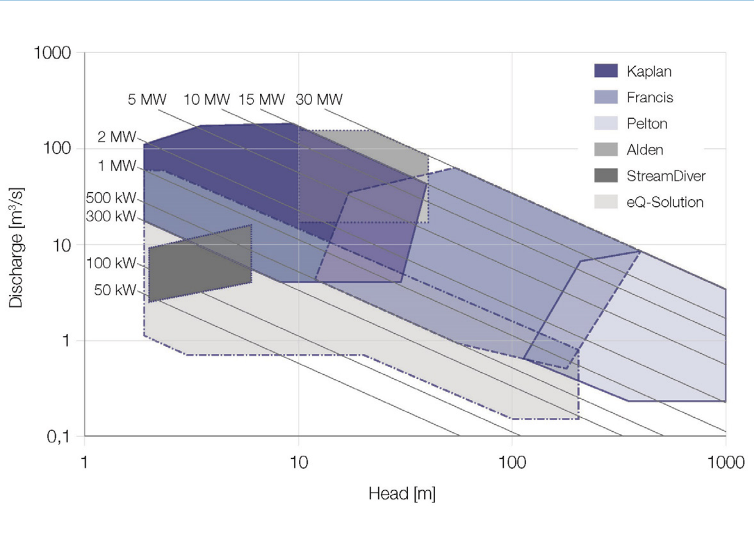


Figure 2 presents a depiction of different types of small-scale hydropower plants by head height, discharge (flow-rate) and capacity. A large flow-rate and small head characterises large run-of-the-river plants equipped with **Kaplan** turbines, a propeller-type water turbine with adjustable blades. By contrast, low discharge and high head features are typical of mountain-based dam installations driven by **Pelton** turbines, in which water passes through nozzles and strikes spoon-shaped buckets arranged on the periphery of a wheel. Intermediate flow-rates and head heights are usually equipped with **Francis** turbines, in which the water comes to the turbine under immense pressure and the energy is extracted from the water by the turbine blades.

The world's largest operating hydropower plant is the Three Gorges plant in China with a capacity of 22.5 GW. The plant generated 98.1 TWh in 2012 (IHA, 2013). The second largest hydropower plant is Itaipu in Brazil/Paraguay, with a 14 GW capacity and a generation of 98.2 TWh in 2012 (Itaipu Binacional, n.d.).

Pumped storage plants consist of two or more natural or artificial (dams) reservoirs at different elevations. When electricity generation exceeds grid demand, the energy is stored by pumping water from the lower to the higher reservoir. During peak electricity demand periods, water flows back to the lower reservoir through the turbine, thus generating electricity. In these kinds of plants, reversible Francis devices are used both for pumping water and for generating electricity. The energy conversion efficiency of recently pumped hydropower is over 80% (MWH,

Figure 2: Types of small hydropower by head height, discharge, or capacity (Voith, 2013)



2009). Pumped storage plants can be combined with intermittent renewable electricity sources. They can also serve as an optimal complement to nuclear-based electricity designed for base-load operation, but with only limited capability to adapt to daily and seasonal load fluctuations.

Currently, pumped storage capacity worldwide amounts to about 140 GW_e. In the European Union, there are 45 GW_e of pumped storage capacity. In Asia, the leading pumped hydropower countries are Japan (30 GW_e) and China (24 GW_e). The United States also has a significant volume of the pumped storage capacity (20 GW_e).

Hydropower generation plants do not produce CO_2 emissions, other than those associated with materials and construction. However, there are concerns about GHG emissions from reservoirs, both from the decomposition of organic material inundated initially, and organic material from further upstream, deposited throughout the lifetime of a large hydropower scheme.

Many hydropower plants were built in the early decades of the 20th century and are still in operation, although most of them have undergone rehabilitation, modernisation or re-development. The era of *really* large hydropower projects began in the 1930s in North America and has since spread worldwide. Today's major projects under construction are located in China, Brazil, India, Myanmar, Ethiopia and Pakistan. Significant potential remains around the world, both for developing a large number of small hydropower projects and for upgrading existing power plants and dams.

Current hydropower growth options can be categorised into three types: **Large hydropower** (>10 MW_e); **small hydropower** (≤10 MW_e) with mini-hydro (100 kW_e to 1 MW_e) as a sub-category; and **upgrading potential at existing hydropower plants** and dams.

The market for large hydropower plants is dominated by a few manufacturers of large equipment and a number of suppliers of auxiliary components and systems. Over the past decades, no major breakthroughs have occurred in the basic machinery; however, computer technology has led to significant improvements in many areas, such as monitoring, diagnostics, protection and control. Manufacturers and suppliers need to invest significant resources into research and development (R&D) to meet advances in technology and deal with market competition. Also, large hydropower plants may have a considerable impact on environmental and socioeconomic aspects at the regional level. Therefore, the link between industry, R&D and policy institutions is important to the development of this energy sector. Throughout all development stages, the stakeholder involvement—especially local residents who live in areas adjacent to the potential site—is crucial.

Unlike large plants, small-scale hydropower installations comprise a huge variety of designs, layouts, equipment and materials. Therefore, state-of-the-art technologies, knowledge and design experience are key to fully exploiting local resources at competitive costs and without significant adverse environmental impact.

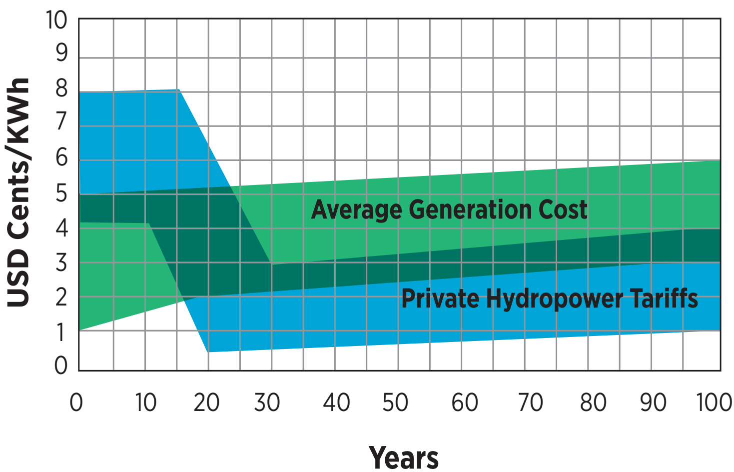
Upgrading offers a way to maximise the energy produced from existing hydropower plants and may offer a less expensive opportunity to increase hydro-power production. Gains of between 5%-10% are realistic, cost-effective targets for most hydropower plants. Potential gains could also be higher at locations where non-generating dams are available. Investment in repowering projects, however, involves risks, both technical and legal (*e.g.* risks associated with the re-licensing of existing installations, often designed several decades ago, with only limited records of technical docu-mentation). As a result, significant potential is left untapped. However, today's technologies allow for an accurate analysis of geology and hydrology, as well as precise assessments of potential gains.

Costs

Existing hydropower is one of the most cost-effective methods to generate electricity. Most plants were built a long time ago and the initial investment for dams and hydro-geological infra-structure has meanwhile been fully amortized. After this amortization, the remaining costs have to do with operation and O&M, and the possible replacement of machinery components after several decades of operation (Figure 3). Small hydropower plants may be operated for around 50 years without substantial replacement costs.

Hydropower generating facilities need long lead times for their development and construction. The investment costs for new hydropower installations, which include the civil engineering works and electro-mechanical components, are highly site-dependent. Civil engineering works include dams and reservoir construction, tunnelling and canal construction, powerhouse construction, site access infrastructure and grid connections, the cost of which depends largely on local labour and materials costs. Contract and other developer costs, such as

Figure 3: Hydro generation costs and investment amortisation (Jianda and Xiaozhang, 2003)



planning and feasibility assessments, environmental impact analyses, licensing, environmental protection, water quality monitoring, etc., are also needed. The electro-mechanical components include turbines, generators, transformers, cabling and control systems. The cost of these components, while reflecting international market prices, does not have much impact on final investment costs.

The total installed cost for a large-scale hydropower project typically ranges from a low of USD 1000/kW upto around USD 3 500/kW. However, exceptions abound. If the site is far from the transmission line and without access and infrastructure, the cost may be significantly higher than USD 3 500/kW. A recent study shows the total installed cost of large-scale hydropower facilities with storage range from as low as USD 1050/kW to as high as USD 7 650/kW. The investment cost of small-scale hydropower plants of 1-10 MW range from less than USD 1000/kW to about USD 4 000/kW. However, the cost of very small-scale hydropower plants of less than 1 MW is significantly higher compared to larger plants, (*i.e.* from USD 3 400/kW to USD 10 000/kW or more).

Hydropower systems usually require only minimal maintenance and have low operation costs. Annual O&M costs for typical hydropower plants ranges 1%-4% of investment costs per kW per year. The O&M costs of large hydropower plants typically range from around 2%-2.5% (a recent study shows average O&M costs for a large hydropower plant is USD 45/kW/year (Ecofys, *et al.*, 2011)) while small-scale hydro can range from 1%- 6%. Data recently collected by IRENA and GIZ show O&M costs for small-scale hydropower ranging between USD 40-50/kW/year (1-10 MW) and from USD 45-250/kW/year (below 1 MW).

A recent IRENA study (IRENA, 2012) shows that the typical ranges of levelised cost of electricity (LCOE) are from USD 0.02-0.19/kWh for large hydropower projects, from USD 0.02- 0.10/KWh for small-scale hydropower and USD 0.27/kWh or more for very small-scale hydropower plants.

The cost of pumped storage systems also depends strongly on the site configuration. The operational service of pumped hydropower plants is also a key parameter for assessing overall operating costs. No cost reduction is expected from technology learning since pumped hydro is a mature technology and is virtually the same in all hydropower plants. The current capital cost of new pumped hydro facilities is estimated to range between USD 2 000–4 000/kW.

Potential and Barriers

The global technical hydropower potential is around 15 000 TWh per year. Half of this potential is located in Asia and about 20% of it is located in Latin America. A large number of sites remains in the world with untapped potential. Even in the most hydropower-developed regions, Europe, the undeveloped potential remains around half of the total potential. Around 1067 GW_e of hydropower capacity are currently in operation, including about 100 GW_e of pumped hydropower plants. The global technical potential of small hydropower is estimated 150-200 GW_e. Only about 20% of this potential has been exploited to date.

Large hydropower projects can be controversial because they may: adversely affect water availability over large geographic regions; inundate valuable ecosystems; force the relocation of population groups against their will, and/or require a large electricity transmission infrastructure. New, less-intrusive, low-head turbines are now being developed for smaller reservoirs. Hydropower usually depends on rainfall in the upstream catchment area and reserve capacity may be needed to compensate for periods of low precipitation. This may increase the investment cost. Major hydropower issues include: public acceptance, high initial investment costs and long payback periods, long approval and construction cycles, and long lead times to obtain or renew concession rights and grid connections. Other barriers, such as stringent environmental standards for water management, can also hamper hydropower development. Coherent policies and simplified administrative procedures are needed.

Significant advances in hydropower technology promise further positive developments. However, the implementation of these advances is often slow and R&D investment insufficient. This is partially due to the misperception that hydropower is a mature technology and offers few upgrading prospects.

While increasing energy supply from hydropower does not require technological breakthroughs, significant R&D, capital investment and govern-mental support are essential to improve technology and public acceptance. Table 1 provides R&D priorities for both large and small hydropower (IEA, 2008). R&D and technical advances are also required for small hydropower, notably equipment design, materials and control systems. One priority is the development of less expensive technologies for small-capacity and low-head applications to enable the exploitation of more modest resources. Key data for hydropower can also be found in Table 2.

Table 1: Technology advances for hydropower (IEA, 2008)

	Large hydro	Small hydro
Equipment	Low-head technologies, including in-stream flow, advanced equipment and materials	Low-impact turbines for fish populations; Low-head technologies; In-stream flow technologies
O&M	Maintenance-free and remote operations	Package plants with limited O&M
Storage and hybrid tech.		Wind-hydro and Hydrogen-hydro systems

Table 2: Summary Table: Key Data and Figures for Hydropower Technology

Technical Performance	**Typical current international values and ranges**		
Energy input	Hydro power		
Output	Electricity		
Technologies	Very small hydro power (VSHP, up to 1 MW_e)	Small hydro power (SHP, 1–10 MW_e)	Large hydro power (LHP, >10 MW_e)
Efficiency (turbine, Cp max), %	Up to 92	Up to 92	Up to 92
Construction time, months	6–10	10–18	18–96
Technical lifetime, yr.	Up to 100		
Load (capacity) factor, %	40–60 (50)	34–56 (45)	34–56 (45)
Max. (plant) availability, %	98	98	98
Typical (capacity) size, MW_e	0.5	5	50
(Existing) capacity, GW_e	75		925
Environmental Impact			
CO_2 and other GHG emissions, kg/MWh	Negligible		under investigation [1]
Costs (USD 2010)			
Investment cost, USD/kW	3 400–10 000 or more	1 000–4 000	1 050–7 650
O&M cost USD/kW/yr.	45–250 or more	40–50	45 (average)
Economic lifetime, yr.	30		
Interest rate, %	10		
Production cost, USD/MWh	270 or more	20–100	20 – 190

[1] *United Nations Educational, Scientific and Cultural Organisation (UNESCO), the International Hydropower Association and the International Energy Agency are jointly investigating under the IEA Implementing Agreement for Hydropower Technologies and Programmes*

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