Hydropower in the Sustainable Energy Mix

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Abstract

The technical potential for hydropower worldwide is between 31 petawatt-hours a year (PWh/y) to 127 PWh/y, while the economic potential is between 9 PWh/y to 15 PWh/y, the report notes. Hydropower, which is the dominant component of renewable energy, is also under the threat of climate change. Climate change has a large impact on water resources and thus on hydropower. Hydropower generation is closely linked to the regional hydrological conditions of a watershed and reacts sensitively to seasonal changes in water quantity. Hydropower is one of the oldest sources of mechanical power and the largest source of renewable electricity generation in use. Global capacity is around 1300 GW. Hydropower is site-specific and so each project will be unique. Hydropower plants are classified according to their size into micro, mini, small, and large hydropower. In terms of generating the capacity the large plants are the most important. These can be either dam and reservoir plants or run-of-river stations. The latter are the easiest to construct and least disruptive, but the former stores energy and is therefore much more flexible in the way it can be used. Energy is taken from hydropower plants through turbines and a number of designs such as Pelton, Francis and Propeller turbine exist to exploit different head heights of water. Most hydropower developments have environmental effects which must be taken into account before constructionHydropower potential is a function of available water and suitable terrain The main advantages of hydropower are low unit cost, low emissions, ease of control and storage. The challenges of hydropower are huge land requirements for storage, soil erosion, ecosystem disturbance and seasonal variability. About 75,000 hectares of land and 14 trillion liters of water are required on average basis to produce 1 billion kWh annually Hydropower plants have a reservoir developed behind a dam to supply water to the hydraulic turbine for generation of a highly flexible, dispatchable electricity supply. Hydropower can be combined with wind, solar and other sources to supply reliable steady and affordable grid electricity. Hydropower can also be exploited from run-of-the-river resources which have less environmental impact but with overreliance on steady supply of rainwater whose supply is unsteady and unpredictable. Apart from power generation, reservoirs can control floods, supply water, and power from stored water even during drought. Hydroelectric electric power plants are useful for grid electricity sustainability particularly during peak hours where plants that generate flexible and cheaper electricity are on high demand.

Keywords
Global warming; renewable sources; wind energy; climate change

1. Introduction

Hydropower is a renewable energy source where electrical energy is derived from the potential energy of water moving from high to lower elevation. Hydropower is a mature technology and widely used; in 2016, a total of 159 countries in the world reported to have developed hydropower. Hydropower is among the most efficient technologies for production of renewable electrical energy, with a typical efficiency of 90% or better for, “water-to-wire.” Hydropower is cost competitive, and is today the only renewable technology that can produce electricity at equal or lower cost, compared to thermal energy sources like coal, oil, or gas, typically in the range of US2–5 c $(kWh)^{-1}$ (2–5 US cents per kilowatt hour)(Mohamed, 2021).

Hydropower has a high potential for carbon emissions reductions in the global electricity system due to low greenhouse gas emissions (GHG), and a large potential for further capacity increase with low generation cost, compared to both other renewables and to thermal power plants. In total, generation by hydropower contributed nearly

17% of the worldwide electricity supply in 2016, implying that > 1 billion people covered their electricity demand from hydropower. Hydropower is the third largest source of electricity generation, behind coal (39%) and natural gas (22%) but far ahead of nuclear (10%)(Mohamed, 2021)

Hydropower is the largest source of renewable energy in the electricity sector with a share of 68% of the renewables, more than twice all other renewables combined (32%). The technical potential for increased hydropower generation is large enough to meet substantial further deployment both in the medium (2030) and long term (2050). A realistic scenario is to double the annual generation (4102 TWh in 2016) to over 8000 TWh by 2050.

Adding to its contribution to energy generation, hydropower has a vital role in supporting grid stability, security of supply, energy storage, and balancing unregulated generation from other renewables like wind and solar power. In addition to energy and grid services, hydro reservoirs can deliver other important services such as water supply, irrigation, flood control, navigation, and recreation. Environmental and social concerns, unless carefully managed, represent challenges for further deployment of hydropower(Killingtveit, 2019).

The first known hydropower plant (HPP) was installed in a house in Cragside, Rothbury, England, in 1870. Industrial use of hydropower started in 1880 in Grand Rapids, Michigan, when a dynamo driven by a water turbine was used to provide lighting. A breakthrough came when an electric generator was coupled to the water turbine and created the world's first hydroelectric power station (of 12.5-kW capacity) which was commissioned on September 30, 1882, on Fox River at the Vulcan Street Plant, Appleton, Wisconsin, United States, lighting two paper mills and a residence. Early hydropower plants were much more reliable and efficient than the fossil-fuel-fired power plants, resulting in a proliferation of small- to medium-sized hydropower stations distributed wherever there was an adequate supply of water and a need for electricity. By 1886, there were 45 hydroelectric power plants in operation in United States. Many other countries followed suit, such as Norway, where the first hydropower plant began operation in 1885 in the town Skien. Only a few years later, in 1890, the town of Hammerfest, north of the Arctic circle in Norway, had electric streetlights supplied from a municipal hydropower system. By the end of the century, 14 towns in Norway had electricity supplied from hydropower(Killingtveit, 2019).

2. Global status of Hydropower

Hydropower is a form of energy obtained from the flowing of water. Waterpower is one of the most cost-effective ways to generate electrical energy and is often the favoured technique when available (Mekonnen and Hoekstra, 2011). For example, hydropower accounts for 99% of all the electricity generated in Norway (Bakken et al., 2012). In China, the Three Gorges Dam, with a capacity of 22.5 GW, is the world's largest hydroelectric project. It generates between 80 and 100 terawatt-hours of electricity per year, enough to power between 70 and 80 million homes (Zarfl et al., 2015; Heming et al., 2001). The use of hydropower, as an example, has significantly enhanced energy access in Cambodia, where the power generated from hydropower increased from 32 to 4370 GWh between 2010 and 2019 (Baird and Green, 2020). It is essential to mention that micro-hydropower projects on a small scale can make a tremendous difference in rural areas (Fujii et al., 2017). Even though hydropower accounted for the largest share of global renewable power capacity, with a cumulative capacity of 1211 GW in 2020, the annual increase in hydropower electricity is much less than solar and wind energy in recent years. Overall, the installed capacity of hydropower energy worldwide is shown in Figure 1(International Renewable Energy Agency, 2021).(Al-Shetwi, 2022; Kabeyi & Olanrewaju, 2023)

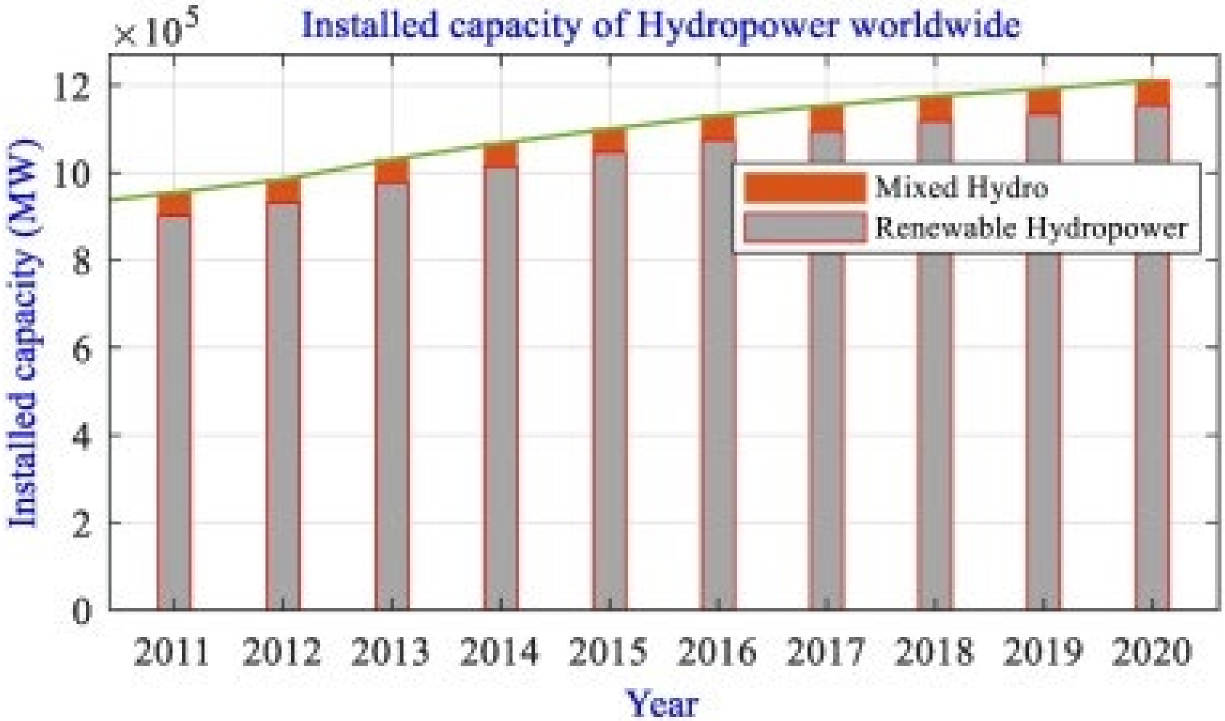

Figure1. Global share of hydropower energy 2011–2020

Figure 1 shows the global status of hydropower between 2011 and 2020 where it increased from about 9 x105 to 12x 105 MW. It is dominated by renewable hydro which is over 90% of the installed capacity while the mixed hydro like pumped hydro accounts for the reminder.

3. Hydro Power Plants

Hydropower, hydraulic power, hydrokinetic power, hydroelectricity or water power is power that is derived from the force or energy of falling water, which is then harnessed for useful purposes. For thousands of years, hydropower has been used for irrigation and the operation of various mechanical devices, such as watermills, sawmills, textile mills, dock cranes, and domestic elevators. In the last century, the term began to be associated with the modern development of hydro-electric power. This energy can be transmitted considerable distance between where it is created to where it is consumed (El Bassam et al., 2013).

Hydropower facilities are classified into three types of hydropower facilities: diversion, impoundment, and pumped storage. Not all dams are built for hydropower and are useful for pumping renewable energy to the grid. The US with 90,000 dams, has less than 2,300 used for power generation in 2020. Other applications of dams include recreation, flood control stock/farm ponds, irrigation, and water supply. Based on sizes, hydropower plants hydropower plants have different sizes (Figure 2) ranging from small systems for a single home or village to large power stations for electricity supply (Energy Efficiency & Renewable Energy, 2021)

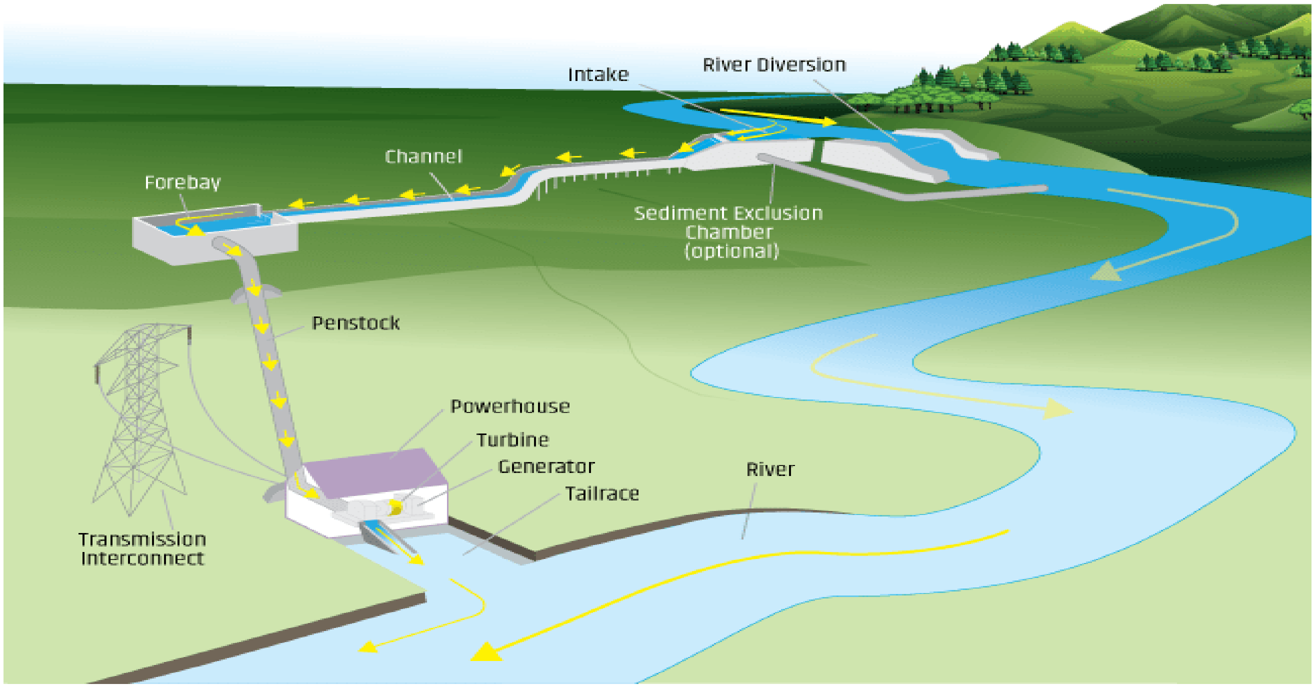

Figure 2. Sizes of Hydroelectric Power Plants

3.1. Size of Hydropower plants

Hydropower plants range from large power plants supplying power to many consumers, to small and even 'micro' plants, that are operated by individuals for their own energy needs or to sell power to utilities.

i.) Large Hydropower

Large power plants vary, in capacity but generally greater than 30 megawatts (MW).

ii.) Small Hydropower

Small hydro power plants generally vary between 100 kilowatts and 10 MW.

iii.) Micro Hydropower

Micro hydro power plants are small and in capacity up to 100 kilowatts. A small or micro hydroelectric power system may generate power for a single home, farm, ranch, or village.

3.2. Run off River Power plant/Diversion

A diversion, which is also called a "run-of-river" facility, directs a portion of a river via a canal and/or a penstock to utilize the natural decline of the riverbed elevation to for power generation. A penstock is used to direct the flow of water to turbines where water flow is regulated by gates, valves, to control generation. Such a system may not require a dam for operation(Energy Efficiency & Renewable Energy, 2022b). Typically, run-of-river power plant does not have storage facility or may have quite a little which implies that they based on the river flow characteristics and have no water storage capability which seriously inhibits their dispatch capability in generation.

A run of river plant without pondage has no water storage and therefore, just like wind, it utilises water as it comes without any regulation Since the system has no control during flooding or during low electricity demand, the result is wastage of excess water hence the utility such hydro power plants is significantly less than other types. However, during normal water flow, the runoff river power plants can supply base load power, and peak demands when the flow reduces (Kuriqi et al., 2021). The firm capacity of the power plants is influenced by the minimum flow of the river. Head water elevation keep fluctuating with river flow conditions, but the plants may be made to supply the base load. Electricity generation is only done when there is sufficient water flow in the river. Therefore, when the river does not have sufficient water, generation is reduced as water does not flow through the intake structure to the turbine. .These hydro schemes may be standalone systems in isolated areas, or can be grid connected(Sharma & Singh, 2013). Figure 3 demonstrates a river run-off hydropower plant.

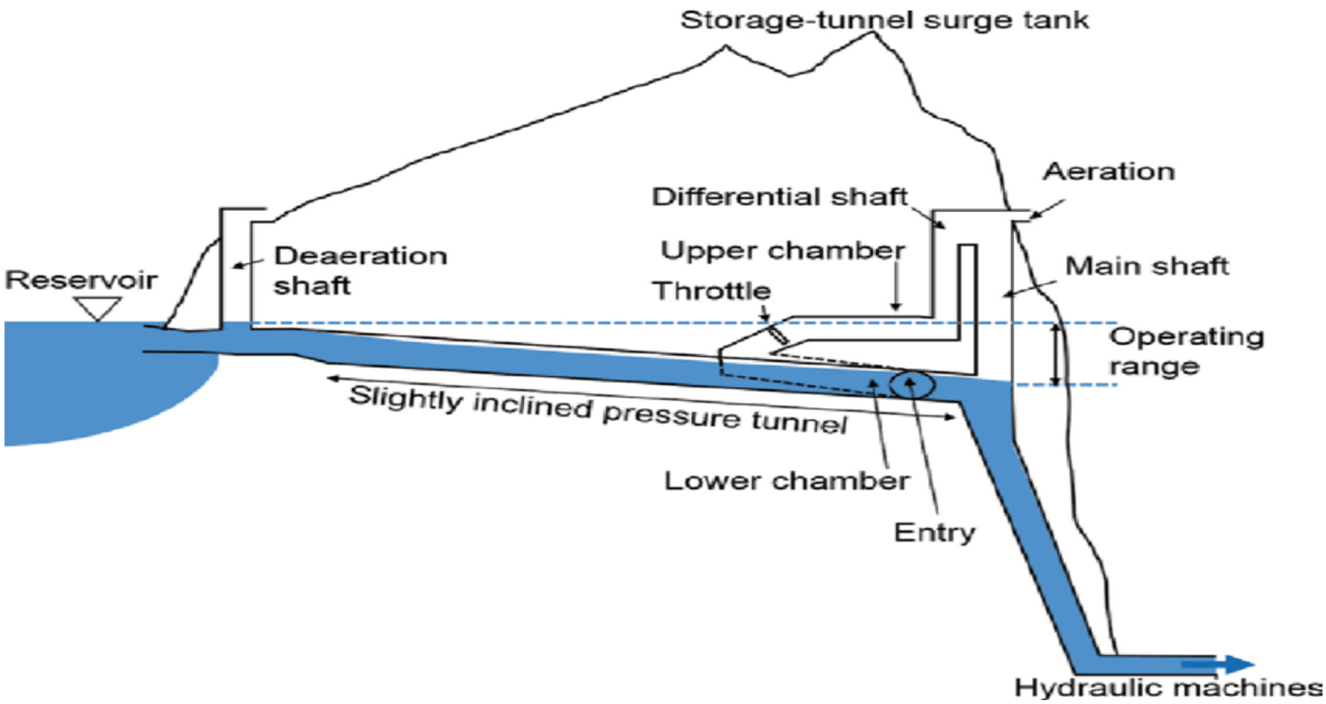

Figure 3. A river run-off hydropower system

From Figure 3, it is noted that the main elements of a river runoff plant are the river or water source, the inclined tunnel or penstock and hydraulic turbines.

3.3. Hydro with Storage/ Impoundment

These power plants are the most common type of hydroelectric power plants. An impoundment facility is typically a large hydropower plant using a dam to store water in a reservoir. Power is generated by releasing water from the reservoir to flow through a turbine which is coupled to an electric generator. The operation of the power plant is made in a manner to meet power demand, flood control, fish recreation, and other environmental and water quality needs(Energy Efficiency & Renewable Energy, 2022b).

These hydro power plants, generally use water stored behind a dam which creates reservoir from which controlled flow is allowed through tunnels from where it is distributed to penstocks which t deliver water to the turbine. Important elements of a hydropower plants are trash racks used to stop foreign matter from flowing into the tunnels and turbines., the surge installed just before the valve house to prevents sudden pressure rise in the penstock in case of drop in turbine load and also to deliver extra water to the turbine when load suddenly rises more than normal flow from the storage (Figure 4). An electrically controlled valve controls flow of water through the hydraulic turbine which is coupled generator in the power house for power generation then used water is discharged to the tail race(Hegde, 2015).

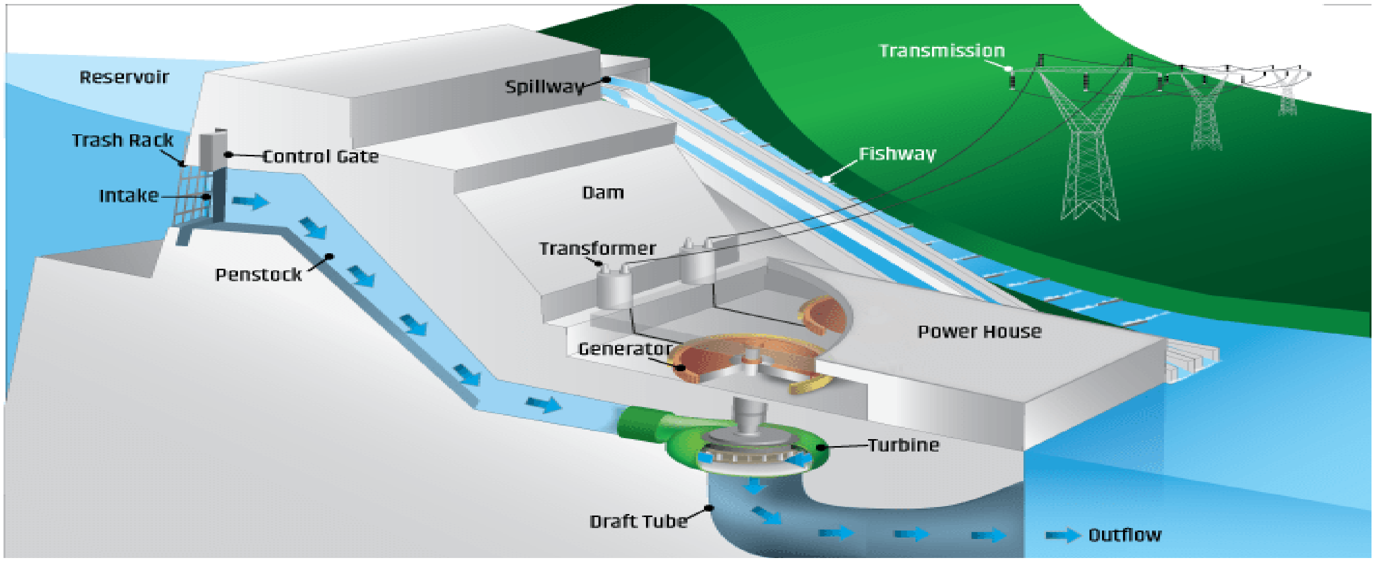

Figure 4. Power generation

3.4. Pumped Storage Hydropower Plants/Diversion

Pumped-storage hydroelectricity (PSH), or pumped hydroelectric energy storage (PHES), is a storage for hydroelectric used mainly for load balancing. Energy is stored in the form of gravitational potential energy of water which is pumped from a lower elevation reservoir to a higher elevation reservoir ready for use when needed. Pumping make the plant a net consumer of energy overall, but it capitalizes on low electricity price during off peak to pump water which is used to generate power for sell during times of high electricity price hence generates revenue for the facility and helps balance power(Rehman et al., 2015).

The pumped-storage hydroelectricity enables uptake of electricity from intermittent sources and other renewables, or excess electricity from continuous base-load plants like nuclear and coal to be saved use at peak demand periods. The storage used by pumped storage is quite small compared to conventional hydroelectric dams and the plants often operate for less than half a day(Rehman et al., 2015). Pumped storage has largest-capacity form of grid energy storage available globally and accounted for about 95% of storage globally in 2020, with a total installed capacity of over 181 GW. The round trip energy efficiency of PSH varies between 70%- 87%. The need for both a geographical height and water availability limit location to often hilly or mountainous regions, and potentially with natural beauty which ,make PSH susceptible to social and ecological concerns(Rehman et al., 2015)

Pumped storage hydropower (PSH) is a hydroelectric energy storage usually equipped with two water reservoirs at different elevations to enable power generation as water flows through a turbine from the upper storage to lower storage during discharge. Power is needed to pump the water back to the upper reservoir during recharging. PSH is like a giant battery, storing energy in form of water for release when needed. Pumped storage hydropower is currently the most form of energy storage for power grids and plays an important role in increased uptake of renewable energy sources by electricity grids(Energy Efficiency & Renewable Energy, 2022a)

The first recorded case of umped storage hydro (PSH) was in Italy and Switzerland in the 1890s. In the US, it was first used in 1930 and currently accounts for about 93% of all utility-scale energy storage in the US with at least 43 PSH plants and potential to increase the PSH plants to more than double current capacity (Energy Efficiency & Renewable Energy, 2022a)

Pumped storage hydro (PSH) can be classified as open loop or closed loop. In the open-loop PSH, we have an ongoing hydrologic connection to a natural source of water like a river, while in the closed loop, the two reservoirs are not connected to an outside body water source or water body of water (Figure 5)(Energy Efficiency & Renewable Energy, 2022a).

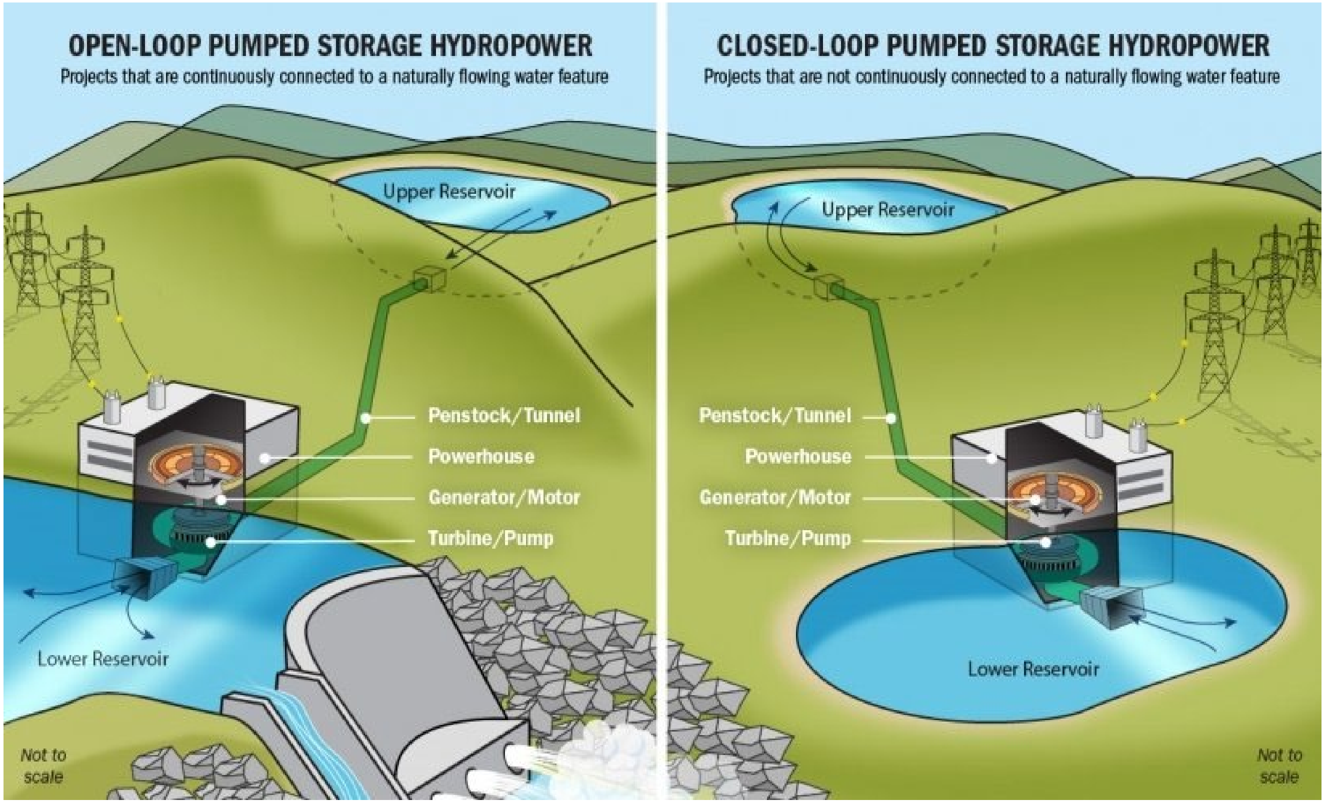

Figure 5. Pumped storage hydro

4. Hydropower Turbines

The two main types of hydropower turbines are reaction and impulse turbines. The selection of turbines is influenced by the water height, velocity of flow and the discharge at the site. Other factors are turbine efficiency, cost and depth of turbine installation.

(Energy Efficiency & Renewable Energy, 2022c).

4.1. Reaction Turbine

Reaction turbines generate power from a combination of forces of pressure and moving water. They have a runner installed directly in the water stream, that allows water to flow over the blades instead of striking the blades. Reaction turbines are generally used at sites with lower head and higher flow aerates and the most common type used in power generation(Energy Efficiency & Renewable Energy, 2022c).

The propeller like Kaplan and Francis turbines are the two most common types of reaction turbines (Energy Efficiency & Renewable Energy, 2022c).

4.2. Propeller Turbine

The propeller turbine is equipped with a runner that has three to six blades and operates as water contacts all of the blades constantly. The blades may be fixed or adjustable and the major components are the runner, scroll case, wicket gates, and the draft tube. There are different types of propeller turbines: (Energy Efficiency & Renewable Energy, 2022c).

a.) Bulb turbine

The bulb turbine has the turbine and generator as a sealed unit placed directly in the stream of water (Figure 6).

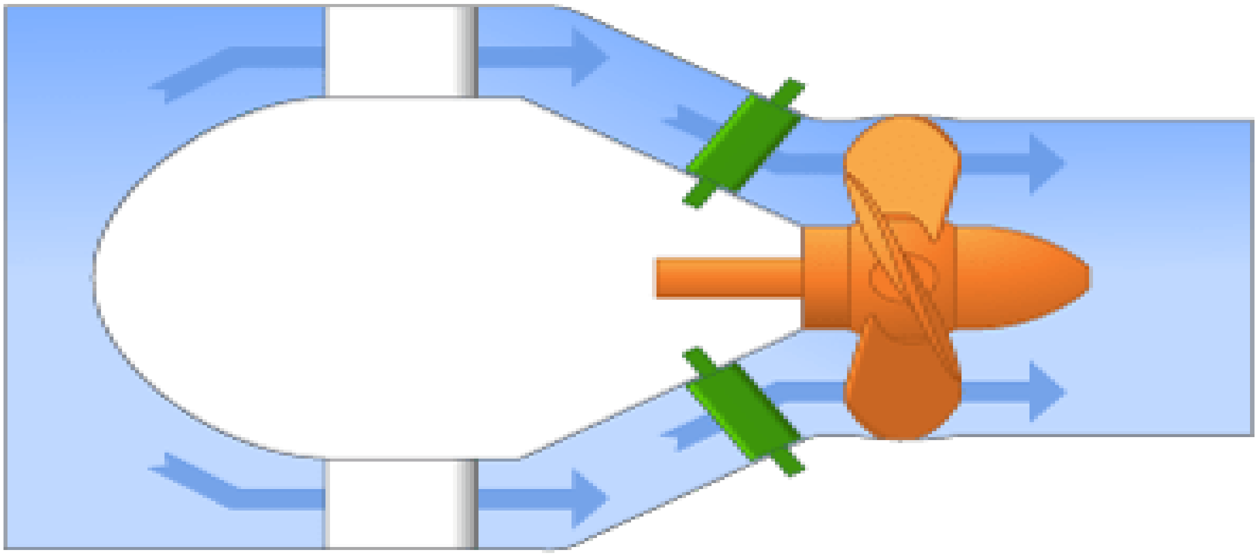

Figure 6. Propeller turbine

b.) Straflo

In the Straflo, the generator is attached directly to the perimeter of the turbine (Figure 7).

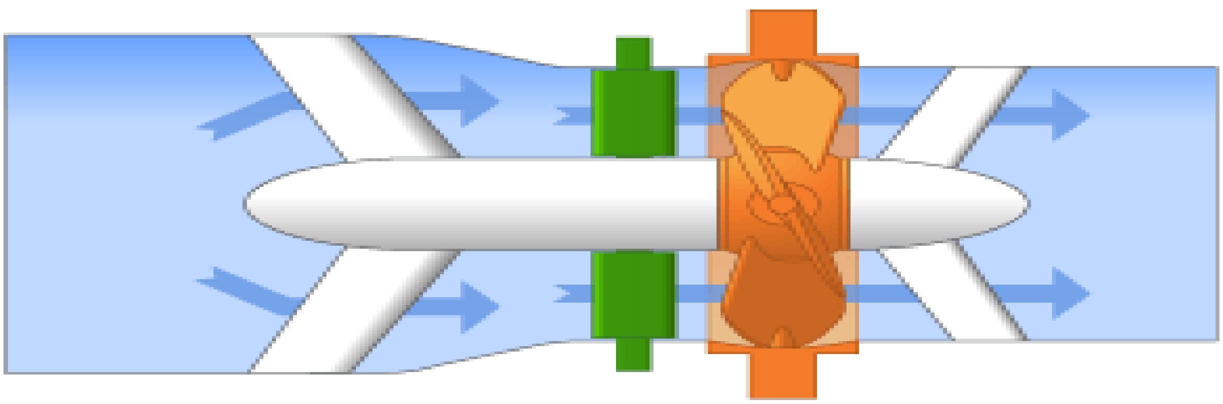

Figure 7. Straflo

a. Tube turbine

In the tube turbine, the penstock bends just before or after the runner which allows a a straight-line connection to the generator(Energy Efficiency & Renewable Energy, 2022c) (Figure 8).

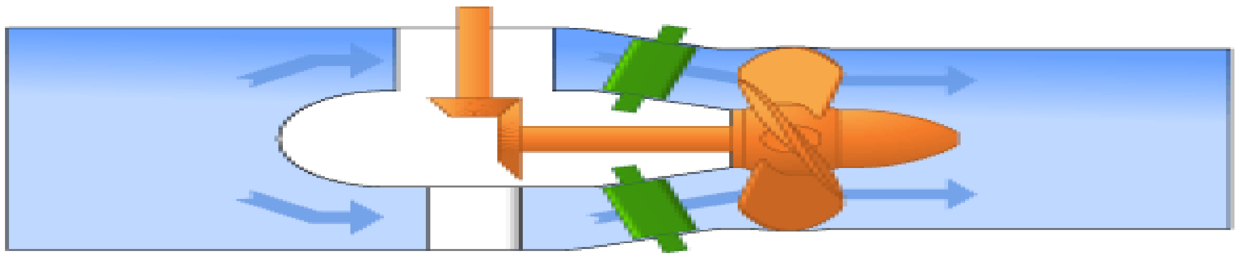

Figure 8. Tube turbine

4.3. Kaplan Turbine

The Kaplan turbine has both the blades and the wicket gates made adjustable which allows them to be effective over a wider range of operating conditions. The Kaplan turbine was developed Viktor Kaplan , an Austrian inventor in 1919 (Figure 9 and Figure 10) (Energy Efficiency & Renewable Energy, 2022c).

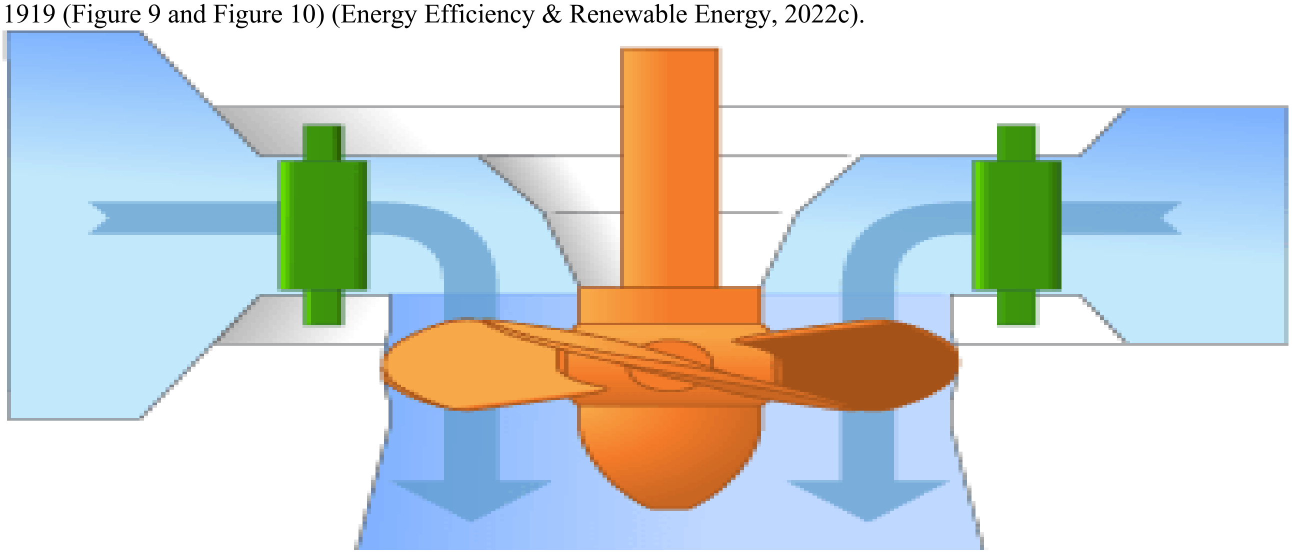

Figure 9. Kaplan turbine

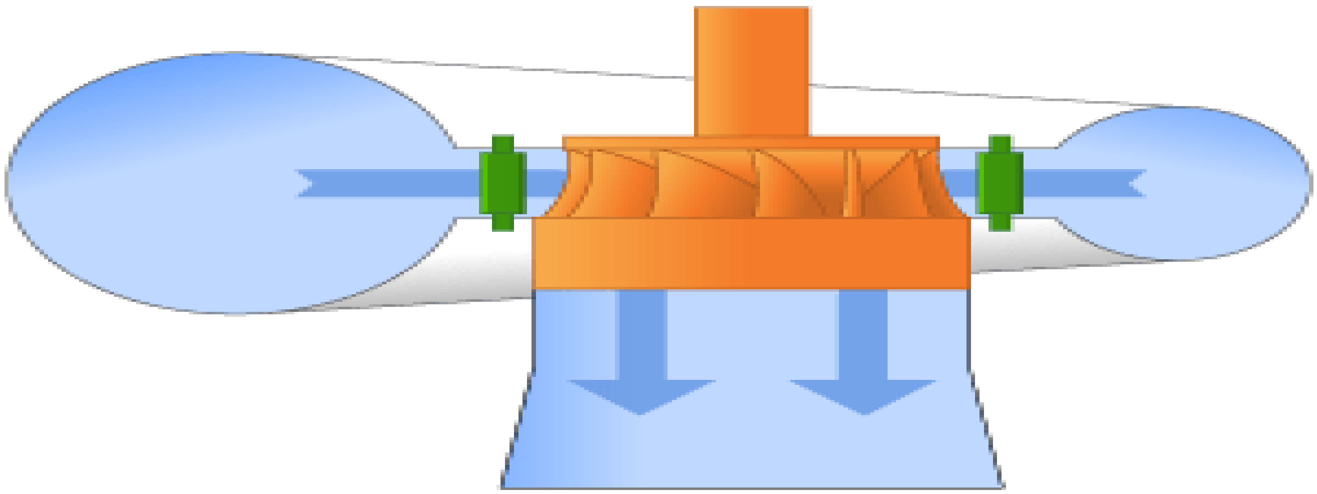

Figure 10. turbine

4.4. Francis Turbine

The Francis turbine was invented by a British-American engineer, named James Francis in 1849. A Francis turbine is equipped with a runner with fixed blades, generally nine or more blades**.** In a Francis turbine, water is introduced above the runner and then all around it then falls through, forcing the blades to rotate**.** The main components of a Francis turbine are the scroll case, wicket gates, and a draft tube. The Francis turbines are ideally applied on medium- to water high-head i.e. 130- to 2,000-foot although they can be used for lower heads too. The turbines work well in both vertical and horizontal axis orientations(Energy Efficiency & Renewable Energy, 2022c).

4.5. Kinetic Turbine

Kinetic energy turbines are also called free-flow turbines, and they generate power from the kinetic energy of flowing water instead of the potential energy from the water head. The turbines are used to generate power from the rivers, man-made channels, tidal waters, or ocean water currents. The turbines do not need a water diversion through pipes, riverbeds, or manmade channels because they use the water stream's natural pathway, although they can still be applied in such conduits as well. The turbines can use existing natural structures without large civil works like bridges, tailraces, and channels(Energy Efficiency & Renewable Energy, 2022c).

4.6. Impulse Turbine

Impulse turbines apply the velocity of the water to turn the runner and discharges at atmospheric pressure (Figure 11). Stream or jet or water hits each bucket on forcing it to rotate without any suction on the turbine down side. The water then, flows out the bottom of the turbine housing. The impulse turbine is ideal where the water head is high but with low-flow rates. Examples of impulse turbines are the are Pelton wheel and the and cross-flow turbine (Energy Efficiency & Renewable Energy, 2022c).

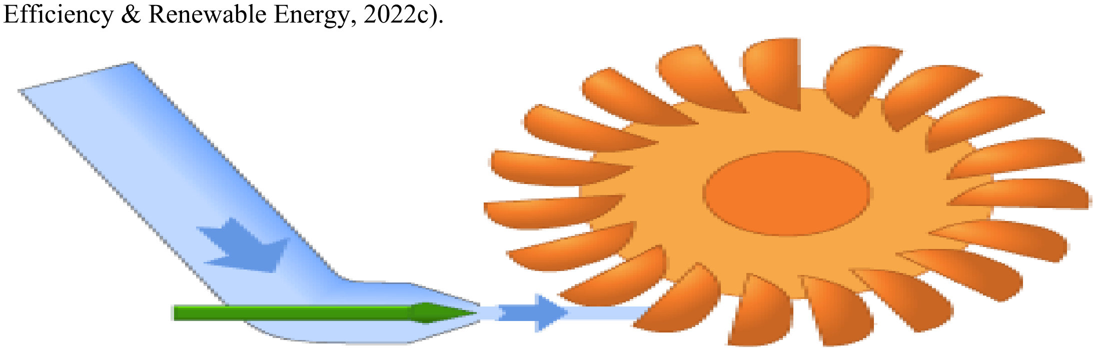

Figure 11. Impulse turbine

4.7. Pelton Turbine
The Pelton turbine was invented by Lester Allan Pelton, an American inventor in the 1870s (Figure 12). In this turbine, one or more free jets discharge water into an aerated space and impinge on the buckets of a runner. Pelton turbines are applied on very high-water heads with low flows. The turbines do not need draft tubes because the runner must be located above the maximum tailwater to allow the operation at atmospheric pressure (Energy Efficiency & Renewable Energy, 2022c).

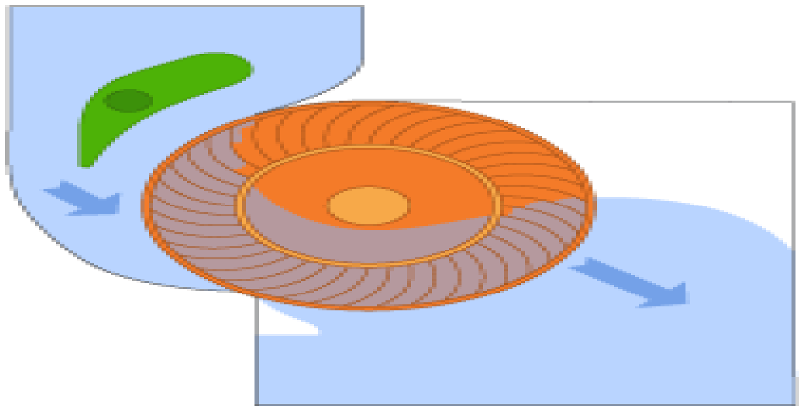

Figure 12. Pelton Turbine

4.8. Crossflow Turbine
Anthony Michell, an Austrian engineer, designed the original crossflow turbine was in the early 1900s. Later, on Donát Bánki, a Hungarian engineer, improved the design, and further improved by Fritz Ossberger, a German engineer. The crossflow turbine is drum-shaped and has an elongated, rectangular section nozzle which is directed against curved vanes on a runner that is cylindrically shaped. The crossflow turbine resembles a squirrel cage blower. The turbine allows water to flow through the blades two times/twice, where in the first pass, the water flows from outside of the blades to the inside; then in the second pass it flows inside back out. Guide vanes of a crossflow turbine are fixed at the entrance to the turbine and is used to direct water to flow into a limited portion of the runner. The turbine was developed to accommodate larger water flows and lower water heads compared with the Pelton wheel (Energy Efficiency & Renewable Energy, 2022c).

5. Environmental Impact
Hydropower and marine power (i.e. tidal energy, ocean thermal energy, and wave energy) are all referred to as water-based power plants (WPPs). In hydropower systems, the water is usually used to drive turbines, which do not directly release GHG (relatively emissions-free). However, water reservoirs (dams) release GHG, albeit at a small percentage, as reported in Lu et al. (2020), Bello et al. (2018) and Faizal et al. (2017). This is because the reservoirs' organic material, like dead plants, decomposes and emits gases such as CH_4 to the water reservoir. In addition, hydropower turbines kill and injure some of the fish that pass through the turbine. However, the new turbine design might minimize fish deaths to less than 2%, compared to 5–10% for the best current turbines, as reported by van Treeck et al. (2021). Also, da Silva et al. reported that da Silva et al. (2018), microbes in decaying vegetation can convert mercury in rocks beneath water reservoir into a water-soluble form. Mercury accumulates in fish, posing a health risk to humans who eat them. Hydropower can also lead to changes to the surrounding landscape, habitat loss, and upstream floods, affecting wildlife habitats, scenic regions, and rich farming land(Al-Shetwi, 2022).

Concerning marine energy, Frid et al. (2012) have reported that when tidal energy is established in coastal estuaries or bays, it can significantly impact the surrounding environment, especially bird feeding locations. Moreover, based on the investigation done by Alipour et al. (2020) and Lin and Yu (2012), offshore tidal stream energy collectors and wave energy contains mid-water column, floating, and devices, each has a unique set of environmental implications. Marine RE may also increase the risk of collisions and underwater noise. The study presented in Willsteed et al. (2017) concluded that electromagnetic field emissions, underwater noise, and collisions are all probable effects of marine RE on coastal ecology and sea animals, especially big predators(Al-Shetwi, 2022).

This section presents the impacts identified for the three large hydropower projects and compares them with the accumulated impacts from the small plants. The impacts are classified in impact categories, varying from 'Very large negative impact' to 'Very large positive impact', according to (Vegvesen, 2006). The type of environmental topics used as basis for comparison are to a very large extent based on the categories given by the guidelines for developing EIAs for hydropower projects;(NVE, 2010), (OED, 2007) and (Jensen et al., 2010), but to some exstent adapted to match the available data of this study. The impacts for Vestsideelvane and Vigdøla are taken directly from the EIAs, where the categorization has been made by consultants, while impact categories for Trollheim hydropower development project have been assessed and set by the authors of this paper. The 'average large HP project'. The environmental impacts of the 27 small-scale hydropower plants have been summed by the authors (expert judgement) and categorised according to (Vegvesen, 2006), as the large projects, in order to provide a uniform basis for comparison(Bakken et al., 2012)

The need for increased energy production in India is high priority and hydroelectric power has been identified as having the greatest potential for achieving energy independence. The Indian government has continually created more streamlined methods for efficient implementa-tion of hydroelectric facilities with an emphasis on small-scale (<25 MW) and micro (<5 MW) facilities in the more remote regions. Himachal Pradesh has effectively achieved one hundred percent electrification due to these initiatives and realized some of the most successful development in the nation with respect to rural electrification and improved infrastructure such as roads, schools, and hospitals. Hydroelectricity, and especially that produced through run of the river type systems, is generally embraced as a renewable source of energy by many established standards. Small scale run of the river facilities are also heralded for the minimal impact to the environment. However, with increased development and construc-tion in continually industrializing areas, measureable human impacts have in-creased felt within the environment and ecosystems. Several studies and papers published by the Indian government, as well as the state government of Himachal Pradesh, identify these impacts as low to nonexistent. In contrast, a growing num-ber of studies refute this claim and deserve consideration. There is a diversity of opinion on this subject. Some secondary sources indicate minimal to non-existent environmental impacts stemming from projects less than 25 MW, considered as Small Hydro Power (SHP); while other sources express significant concern. Inter- views with government officials and researchers in the Indian states of Himachal Pradesh and Uttarakhand as well as in the capital city of Delhi revealed a wide range of views. This paper presents observations and argues for greater exploration of these issues through future research.

6. Conclusion

Hydropower is a form of energy obtained from the flowing of water. Waterpower is one of the most cost-effective ways to generate electrical energy and is often the favoured technique when available (Mekonnen and Hoekstra, 2011). For example, hydropower accounts for 99% of all the electricity generated in Norway (Bakken et al., 2012). In China, the Three Gorges Dam, with a capacity of 22.5 GW, is the world's largest hydroelectric project. It generates between 80 and 100 terawatt-hours of electricity per year, enough to power between 70 and 80 million homes (Zarfl et al., 2015; Heming et al., 2001). The use of hydropower, as an example, has significantly enhanced energy access in Cambodia, where the power generated from hydropower increased from 32 to 4370 GWh between 2010 and 2019 (Baird and Green, 2020). It is essential to mention that micro-hydropower projects on a small scale can make a tremendous difference in rural areas (Fujii et al., 2017). Even though hydropower accounted for the largest share of global renewable power capacity, with a cumulative capacity of 1211 GW in 2020, the annual increase in hydropower electricity is much less than solar and wind energy in recent years. Overall, the installed capacity of hydropower energy worldwide.

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