https://doi.org/10.1051/e3sconf/202338502007

Pumped Storage Hydropower: Technological Implementation, Environmental Consideration, and Potential Growth

Eddie Lou[1, *], Yijin Song[2], Zihan Geng[3], Yunxi Zhao[4]

[1]Philips Academy Andover, Andover, MA, 01810, USA
[2]YK Pao School, Shanghai, 201600, China
[3]BASIS International School Park Lane Harbour, Huizhou, 510682, China
[4]Chinese international school, Hong Kong, China

Abstract: Hydropower is one of the dominating renewable energy sources of the modern era, generating around 17% of the world's total electricity. Pumped storage hydropower in particular is rapidly growing within the industry, making it a topic of interest. This report will give an overview of the history of hydropower as a whole and specifically pumped storage, examine the physical principles and current technological implementations, and discuss the environmental and economic impacts. We have concluded that despite the seemingly long-term investment, pumped storage remains a reliable and necessary form of renewable energy.

1. INTRODUCTION

Hydropower is a prominent player in the industry of renewable energy. It is not only the oldest form of renewable energy, but also the largest, making up 17% of the world's total electricity production. This is more than the rest of the renewable energy sources combined. At USD$0.05 per kilowatt-hour, the cost is also the cheapest out of the other renewable energy sources [1]. Thus, hydropower serves as an affordable and reliable alternative to conventional fossil fuels, despite having some environmental drawbacks on nearby ecosystems and water quality.

In the modern era, hydropower can be divided into three general types: reservoir, run-of- river, and pumped storage [2]. Regardless of the type, hydropower relies on turbines and generators to convert the kinetic energy of the flow of water into electricity [3].

Reservoir systems, commonly in the form of dams, store and redirect the flow of water towards turbines using penstocks. After passing through and generating energy, the water arrives in a lower reservoir. This system can control the amount of water released to the turbines, allowing energy production to adapt to variable needs [2].

Run-of-river, on the other hand, minimally stores water and uses penstocks, meaning the amount of water released is unregulated. Within rivers or streams, the natural flow of water turns the turbines in order to generate electricity. The passing water continues its path after it is used. This system produces less electricity compared to conventional reservoir systems, and its production of energy is also inconsistent depending on the location and time of year [4].

This report will discuss pumped-storage hydropower, which is similar to reservoir systems. Water is also stored and redirected towards turbines, generating energy while flowing to the lower reservoir. However, the water from the lower reservoir can be pumped back to the initial reservoir for future use. The energy required for this process is derived from excess power produced by the reservoir system. When there is a demand for energy, the pump works in reverse as an additional generator. This ability to efficiently use surplus electricity to recycle water makes pumped storage more dependable and flexible compared to reservoir systems [5]. For these reasons, pumped storage is a topic of interest in the field of hydropower.

The following will outline the history of pumped storage hydropower, the physical principles behind its technological implementation, and a detailed system description. The report will conclude with an analysis of its environmental and economic impact, as well as our recommendation for the usage of pumped storage hydropower.

History of Pumped Storage Hydropower: Hydropower dates back 2000 years ago to ancient Greece and Egypt. The Greeks used basic water wheels to grind flour into wheat, and the Egyptians used Archimedes' water screws for irrigation systems [6]. Fast forward to 1832, French engineer Benoît Fourneyron introduced the first successful water turbine [7], and by 1849, the most common hydropower turbine — the Francis turbine — was created by the American engineer, James Francis [8].

The reversible turbines used in pumped storage facilities are Francis Turbines. These turbines are specifically utilized because they can also function as a pump [9]. In order to create this highly efficient turbine, he improved upon previous models; between 1826 and

*Corresponding author email: Eddie.lou24@gmail.com

1840, French engineers Benoit Fourneyron and Jean-Victor Poncelet developed the turbines that could reach efficiencies of up to 80% [7]. Francis used mathematical and scientific principles to optimize the design, resulting in a possible efficiency of 90% to 95% [10].

Decades later, the first instances of pumped storage hydropower were recorded in the 1890s in Switzerland and Italy [11]. These were originally purposed for water management, including the Engweiher pumped storage facility in Switzerland: the oldest working pumped storage plant, built in 1907 [12]. By 1930, the US established its first pumped storage facility in New Milford, Connecticut [11]. During this decade, reversible turbines were utilized, allowing this form of hydropower to become a method of energy production and storage.

In the modern day, pumped storage hydropower has played a significant role within renewable energy. As of 2019, there are now 43 plants, which compose of 93% of all utility- scale energy storage. They yield a combined power capacity of 21.9 GW, approximately enough to power 7 million homes [13]. Pumped storage hydropower is growing almost as fast as all other energy storage methods combined, showing that this industry has great potential for further impact

2. PHYSICS AND TECHNOLOGY PRINCIPLES

There are multiple ways which hydroelectric plants function, but the conventional ones are using the dam reservoir to generate electrical energy. The dam power plants usually constitute three parts of energy conversion: 1. Potential energy of water to kinetic energy of water. 2. Kinetic energy of water to mechanical energy of turbines. 3. Mechanical energy of turbines to electricity.

2.1 Potential energy of water to kinetic energy of water

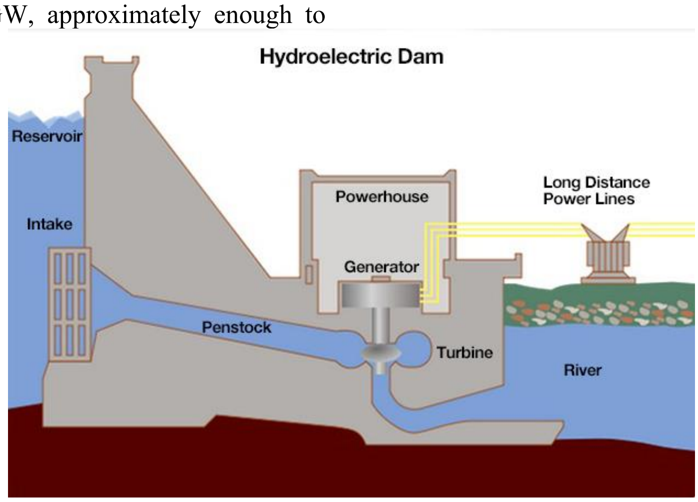

Figure 1: Detailed structure of hydropower dam [14]

Dam power plants usually build up on rivers or water reservoirs with a large volume of water flow, which ensures pre-existing kinetic energy of water as water moves into the dam. However, it largely depends on the differences in height between the penstock, which is a gate that controls water flow, or an enclosed pipe that delivers water to hydro turbines and sewerage systems, and the hydro turbines [15]. This height difference is referred to as the "head" [16]. From the calculation of potential energy generated by the "head", we can determine the total amount of kinetic energy of water that comes to the hydro turbines. The basic formula for energy conversion:

$$GPE = KE \quad (1)$$

$$M(Kg)gH(m) = \frac{1}{2}M(Kg)v_2\,(m_2/s_2) \quad (2)$$

M represents the mass of the stored water, g is the gravitational constant on earth (approximately 9.81N/s^2), H is the height from head to the turbine, and v is the velocity of water flow.

Since the density of water is 1 · 103 kg/m3 , the equation can be rewrite as:

$$1000V(m_3)gH(m) = \frac{1}{2}M(Kg)v_2\,(m_2/s_2) \quad (3)$$

In this case, V represents volume of water.

2.2 Kinetic Energy of water to mechanical energy of the turbines

When the water flows through the tubes or waterways and reaches the generator, the energy of the water flow will turn the turbines, which the row of blades is fitted to some rotating shaft or plate. Water is then passed through the turbine over the blades, causing the inner shaft to rotate. This rotational motion is then transferred to a generator where electricity is generated [17]. The flow rate of water, Q, can be calculated by:

$$Q(m_3/s) = A(m_2)v(m/s) \quad (4)$$

A is the cross-section area of the tube/water way, and v is the velocity of the water flow [18].

2.3 Mechanical energy of turbine to electricity

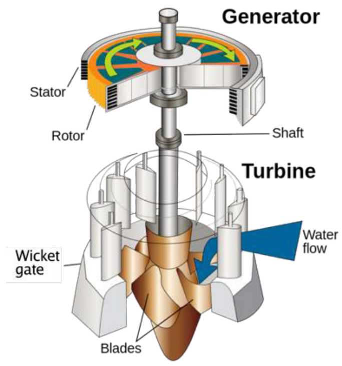

Figure 2: Structure of hydro turbine and generator [19]

When the shaft of a turbine is turned, electric generators are used to transform mechanical or kinetic energy into electric potential difference, also known as voltage. This is done by a process called electromagnetic induction, which originated from Faraday's law. The electricity generator has inserted magnets, which create a magnetic field inside the generator. When water turns the blades, the magnetic field inside the electricity generator or coils will rotate with the blades. Then the magnetic field lines are cut by the coils, creating current in the circuit, thus energy is generated. Basic Formula:

$$E\ (V) = N\frac{d\phi B}{dt} \quad (5)$$

E is the electromotive force (EMF), N is the number of turns made by coil, and $\frac{d\phi B}{dt}$ describes the rate of change of the magnetic flux enclosed by the circuit [20].

2.4 Efficiency consideration and limitation

Table 1: Energy generation efficiency [21]

SI. No.	Particulars	Design	Operating		
01	Unit load (MW)	100	100	75	50
	Component efficiencies				
	Units	%	%	%	%
02	Water conductor efficiency	94.36	97.36	96.50	96.54
03	Hydraulic efficiency of turbine	94.64	93.23	90.64	75.18
04	Volumetric efficiency of turbine	99.99	99.94	99.93	99.91
05	Mechanical efficiency	99.40	99.40	99.40	99.40
06	Generator efficiency	98.67	98.35	98.13	96.54
07	Auxiliary efficiency	98.67	98.35	98.13	96.54
	Auxiliary power				
08	Auxiliary power (% of gross generation)	0.50	0.253	0.422	0.836
	Overall system performance				
09	Gross overall efficiency (%)	87.59	86.74	85.32	69.65
10	Net overall efficiency (%)	87.15	88.52	85.01	69.06
11	Specific water consumption (m/s/MW)	0.452	0.435	0.480	0.624

The energy of moving water is purely mechanical, one of the highest-quality forms of energy, thus it can be converted to electrical energy with near 100% efficiency as there is no thermal energy involved. Since energy may be lost by friction, sound, and a lower actual head, the efficiency of energy conversion usually varies from 75%-95%. To improve the accuracy of the measurement, η, is introduced to represent the efficiency of the power plant [22].

Therefore, the power of the energy generation process is being expressed as:

$$P(w) = 1000 . \text{刀} . Q(m^3/S) . g . H(m) \quad (6)$$

Which can be simplified into:

$$P(Kw) = \eta \cdot Q(m^3\ /S) \cdot g \cdot H(m) \quad (7)$$

3. Technology Implementation

When considering the real-world situation, if the turbine drives the generator directly, only certain rates of rotation are permitted because the alternating voltages from all the power stations contributing to any grid system must have the same frequency. In European countries and many others, the agreed frequency is 50 Hz, and in the US, it is 60 Hz [23]. Thus, the number of turbine rotations should be regulated. The regulation can be done both by controlling flow rate or employing a suitable turbine, which leads to different penstock and turbine management and designs.

3.1 Structure of penstock

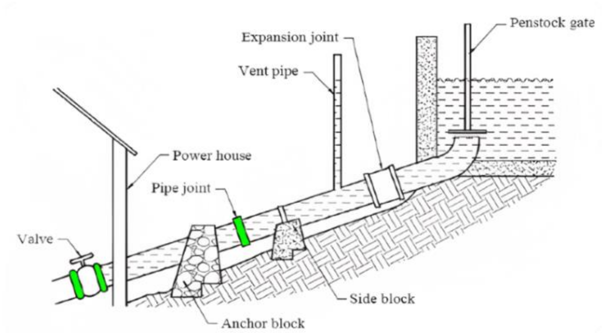

Figure 3: Structure of penstock in hydropower system [24]

Penstocks are pressure vessels in the form of a channel or pipe that carries water from the source to the turbine, which can vary in length and size the maximize the efficiency of hydropower plants or suit the geographic conditions [25]. To control the flow rate to adjust the power output, penstock can be manipulated with a sluice, which is a gate that can be raised and lowered to increase or decrease the amount of water allowed to flow through [26].

Most penstocks are constructed from steel, so they are prone to corrosion mechanisms since they carry water [25]. Also, water flow can carry debris to the penstock, reducing the effective flow rate and harming the channels. Therefore, penstocks generally require regular cleanings to remove debris. During these cleanings, holes, cracks, and other problems can be discovered and fixed. This helps prevent catastrophic dam failures and ensures power plant efficiency [26].

3.2 Different types of turbines

One criterion used to classify turbines is whether the liquid pressure changes when flowing through a turbine after passing though the penstock as penstock can change the pressure of water. Different kinds of turbines can work efficiently in diverse conditions.

(a) Reaction turbine

The reaction turbine directly uses water pressure to move blades instead of relying on the conversion of water pressure to kinetic energy, so reaction turbines need to be submersed in water. This type of turbine functions depending on the fluid velocity and reduction in water pressure which causes a reaction [27]. Reaction turbines are generally used for sites with lower heads and higher flows and are the most common type currently used in the United States. Types of reaction turbines include Kaplan turbines and Francis turbines [28].

(b) Impulse turbine

In impulse turbines, the pressure of the water doesn't change in the turbine. When the water strikes the blades, it changes velocity, leading to a change in momentum, and exerting a force on the turbine blades. These turbines rely on the ability to take all kinetic energy from the water to have high efficiencies. Unlike reaction turbines, impulse turbines do not need to be submerged [27]. An impulse turbine is generally suitable for high-head, low-flow applications. Types of impulse turbines include Pelton turbines, Turgo turbines, and Crossflow turbines [28].

4. Detailed System Description

While there are different forms of hydroelectric power plants such as reservoirs, run-of- river, and in-stream power plant, this paper will focus on the most used pump-storage-type hydropower system due to its convenience of making rapid adjustments. For example, there is one at Bath County in the US. This pump storage system the largest in the world, providing 3000 MW of power generation capacity.

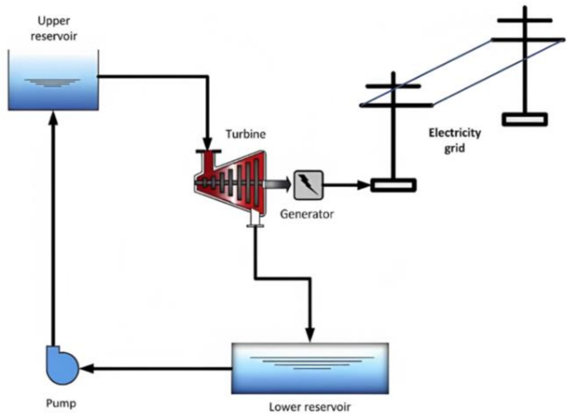

Figure 4: Diagram of a pump storage system [29]

As shown in the illustration above, this system consists of a dam and a reservoir power plant. There is a lower reservoir at the tailrace end to collect the excess water leaving from the powerhouse. To ensure sustainability, a pump is constructed to send the water back to the main reservoir when water levels are low to meet the demand for extra power supplies. Dams are built along rivers to hold massive amounts of water in reservoirs. The stored water in top reservoir is subsequently used in the turbine, and the energy is extracted from water in order to produce mechanical energy. Following that, it is sent to the generator attached to the turbine, turning into electrical energy. The unused water from the turbine is sent into the lower reservoir, and the created electricity is supplied into power system for everyday use. [13]. In this way, the system acts like a battery, storing hydroelectric power when demands are low and providing maximum power during daily and seasonal peak periods.

4.1 Reservoir

It could be an artificial lake or a naturally formed lake whose outflow has been blocked to manage the water level where the water is stored. It regulates the natural streamflow by holding excess water during the wet season and releasing it during future dry season to compensate for the reduction in river flow.

In this system with two reservoirs, identifying the desired site for two reservoirs to be erected is difficult because they must be separated from each other to ensure a suitable distance for sufficient heads required. A high-head system is a preferable choice because it offers higher energy output than a low-head system. [29].

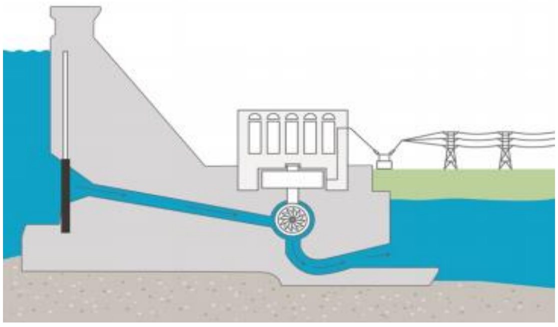

Figure 5: A diagram of a dam's inside structure [35]

4.2 Dam

The dam is responsible for controlling the amount of water that flows out of the reservoir. Importantly, because its weight pushing against the dam creates large pressure, its shape and thickness must be carefully designed to hold the water back and prevent the water from breaking through, even during extreme circumstances when rainfall increases the pressure [29].

4.3 Pump

It produces flow with sufficient force to counteract the pressure from the load at the pump outlet. When a hydraulic pump is operating, a vacuum is formed at the pump inlet, forcing liquid to enter the pump's inlet line from the reservoir. This liquid is then mechanically delivered to the pump output, where it is forced into the hydraulic system. [34].

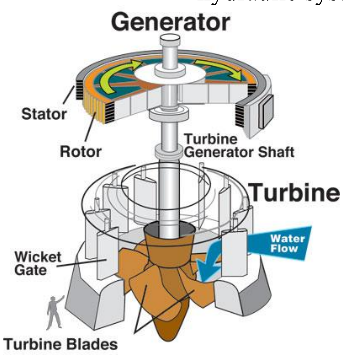

Figure 6: Diagram of a hydroelectric turbine and generator [33]

4.4 Turbine

When water with high pressure enters the turbine through the snail-shell casing (the volute), the pressure is decreased as water curls through the tube with the speed remaining constant. The water then flows through the guide vanes, and its angle is directed at optimal level towards the runner's blades. Because the water crosses the blades with precision some of its spinning velocity is lost. Furthermore, the water is deflected axially when leave the draft tube into the tail race. This produces a reaction force, which allows the turbine to continue spinning. The whole process of changing the direction of water flow reduces the turbine's inner pressure as well [31].

4.5 Generator

There are electromagnets circulated in a generator through direct current wire loops. These loops are wrapped around magnetic steel stacks, also known as field poles, that are installed on the rotor periphery. The turbine shaft, which rotates at a set speed, is attached to the rotor. When the rotor begins to rotate, it moves the field poles past the conductors positioned in the stator, causing electricity to flow, and thus voltage is created at the generator's output terminals. [33].

4.6 Electricity gird

With the electrical energy transformed by the generator, there are two methods of connecting the system to grid panels for further distribution: the first one is using a fixed-speed induction generator, and the second one is through the usage of grid-tied inverters. A fixed-speed induction generator is grid-excited, meaning it can create magnetic field energized by the grid. Thus, the generated electricity is perfectly synchronized with the grid providing the excitation. Nevertheless, if there is a sudden power cut, the excitation will stop, causing the generator to shut down [32].

On the other hand, an inverter is a power-electronic device that converts direct current into alternating current, which makes the generator not controlled by the power grid anymore. The turbine begins operating when the water input is opened. Next, the generator starts to excite, creating alternating current electricity as more water flows through the turbine at increasing rate. The control system that is connected to the inverter then adjusts the flow rate by monitoring the voltage and frequency, which means the generator can spin at different speed depending on the demands. Although the generated electricity is incompatible with the grid, a rectifier will rectify the "dirty AC" from the generator to make it reaches specification, therefore producing perfect grid-synchronized AC electricity [32].

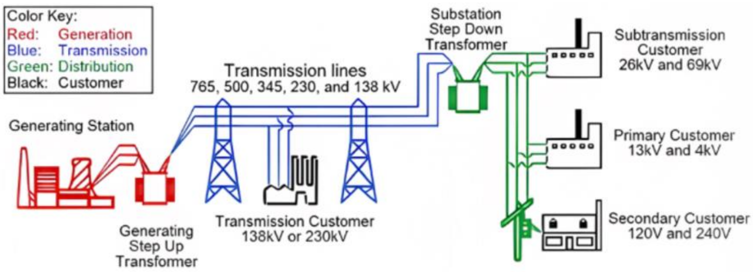

Figure 7: A typical layout of an electrical power grid [30]

As electrical energy is produced through generators, usually at voltages ranging from 11kV up to 25 kV, they are then sent across long distances using high-voltage transmission lines. To improve transmission efficiency, the voltage is increased from 220kV to 765kV by lowering I2 R losses in the transmission lines. The voltage is further stepped down to 11kV at the distribution substations. The power is then delivered using above- or below-ground distribution lines, that are often linked together. In order to deliver the electricity to daily households, distribution transformers are used to further lower the voltage to the utilization level, usually at 120V to 230V, through secondary distribution lines [30].

5. ENVIRONMENTAL IMPACT

Hydropower is a source of renewable energy rising in the world's electricity output index given its renewable, clean, flexible, and environmentally friendly form. Data shows that in 2015, hydropower, which generates an average of 3930 TWh per year and accounts for 16% of the world's total electricity production, represented 78% of the green energy output. The global hydro capacity has been growing gradually at a compound annual rate of 2.7 and is expected to surpass 1200GW in 2022. The wide usage of hydropower in today's environmental scheme demonstrates that hydropower is a substantial source of renewable energy effectively reducing Greenhouse gas emissions and thus slowing the effects of global warming.

Today, fossil fuels (coal, oil, gas, and wood) account for 85% of the total primary energy consumption. The burning of fossil fuels contributes greatly to large-scale greenhouse gases in the atmosphere, which involves the production oof methane from the burning of coal and natural gas as well as the combustion of carbon dioxide [37]. The mass emissions of Greenhouse gases have contributed to climate change and consequences on the hydrological system.

In boreal habitats, hydroelectric power generation factors typically range from 30 to 60 times lower than those for fossil fuel generation. Thus, Renewable energies like Hydropower are important contributors to the reduction of GHG emissions. When compared against conventional energy sources like fossil fuels, Hydropower renewable energies are able to prevent carbon dioxide emissions at the scope of 3GT per year and cut down 9% of global annual carbon dioxide emissions [38]. Alongside, Hydropower plants can mitigate environmental issues like air pollution, global warming, and acid rain - which are typically caused by fossil fuel-driven facilities - as hydropower plants do not emit waste heat and gases.

When compared to traditional energy sources, hydropower may reduce annual CO_2 emissions by around 9% globally and by 3 GT globally. [38] The waste heat and gases that are frequently released by fossil fuel-powered facilities and are the main causes of air pollution, global warming, and acid rain are not produced by hydropower stations. The World Energy Council (WEC) predicts that the carbon dioxide emissions per GWh for hydropower generated by river flow are 3–4 and 10–33, respectively. The figures show that the emissions from traditional thermal power are 100 times lower [36].

According to the United States National Hydropower Association, the utilization of hydropower energy sources can cut out an estimate of two hundred million metric tons of carbon yearly [39]. Moreover, the expansion ofjust half of the world's economically viable hydropower potential could reduce around 13 percent of total emissions. On the other hand, the impact hydropower energies have on the avoided sulfur dioxide is even greater. Although the construction of hydropower stations requires fuel, however, a hydropower system can emit 1000 times less of sulfur dioxide compared to a coal fired plant. An example for pollutants from fossil fuel plants is China, where an estimate of 23 million tons of Sulfur dioxide from thermal power plants are discharged into the atmosphere annually, resulting in 40 percent of the land area being severely affected by acid rain, causing damages to the environment, crops, forests and human health [40].

6. ECONOMIC GROWTH

By far, hydropower is the largest renewable energy all around the world, producing over twice as much energy as wind, and over four times as much as solar energy. Among the various hydropower sources, reservoirs, aka conventional hydro, are created by building a dam across a river or over the outlet to a lake. The average cost of building a dam might vary, ranging mostly between $1,000 and $5,000 per kW , as it depends on the size of the dam and the function of it as well [41]. Thus, a standard dam will expense about $20,000; middle-sized dam will cost around $50,000; even bigger dam projects will cost from $80,000 to $120,000 [42].

Compared to other major renewable energy and fossil fuel sources, hydropower generation has the lowest production cost. According to the International Renewable Energy Agency (IRENA), hydropower is the most flexible energy source available by far. This is because it not only provides the main regulating and balancing capacity in the electricity system, but also responds to the demand fluctuations in a short period of time [43]. Specifically speaking, water levels in bodies of water fluctuate depending on the amount of precipitation of a specific area, which means during a drought these water bodies, such as lakes and rivers, might not provide residents with enough water. Nevertheless, the water level in the reservoir is controlled, so water is always available for farming, drinking and other different uses.

Moreover, dams could help to control flood by collecting water and discharging it into the riverbank; flow-through dam, developed to protect low-lying region from flooding, is an example. In this way, property damage and casualties due to flooding would be avoided.

In addition, economic benefits of reservoirs also include supporting navigation and irrigation and providing a stable system of water transport.

For future developments, modernizing existing hydropower infrastructure could increase efficiency and ensure that plants could still continue to operate in the future. According to Consumer News and Business Channel (CNBC), from now till 2030, $127 billion will be spent on modernizing old plants worldwide, which accounts for nearly one fourth of total global hydropower investment and the majority of investment in Europe and North America [44].

But in other parts of the world, investment is made in the construction of new plants. In 2030, Asia and Africa are expected to account for over 75 percent of new hydropower capacity. Reservoir will make up 56% of the total capacity additions this decade with pumped hydro 29% and run-of-river hydropower 13% [44].

7. CONCLUSIONS

In this paper, hydropower is discussed from various perspectives: its history and the process of its continuous development, the physics of hydropower with specific description of penstock, turbines, etc. and the environmental and economic impact of hydropower. However, even though hydropower's steady energy already complements other renewable energy sources, its overall growth is slowing. According to Shannon Ames, Executive Director of the Low Impact Hydropower Institute, part of the reason it doesn't look as attractive sometimes as solar and wind is because hydropower is licensed and operates for longer times, usually 50 years. But the capital markets don't necessarily appreciate a longer return like that. Therefore, it will be crucial to find the best incentives for the development of pumped storage and hydropower while also making sure that it is done in a sustainable way.

REFERENCES

1. Hydropower Has a Crucial Role in Accelerating Clean Energy Transitions to Achieve Countries' Climate Ambitions Securely - News." IEA, 1 June 2021, https://www.iea.org/news/hydropower-has-a-crucial-role-in-accelerating-clean-energy-transitions-to-achieve-countries-climate-ambitions-securely.
2. "Hydroelectric Plants." Enel Green Power, https://www.enelgreenpower.com/learning-hub/renewable-energies/hydroelectric-energy/hydroelectric-plants.
3. "How Hydropower Works." Energy.gov, https://www.energy.gov/eere/water/how-hydropower-works.
4. Douglas, Tanis. "'Green' Hydro Power: Understanding Impacts, Approvals, and Sustainability of Run-of-River Independent Power Projects in British Columbia." Watershedwatch.org, http://www.watershedwatch.org/home.
5. "Pumped Hydro Storage." Pumped Storage | GE Renewable Energy, https://www.ge.com/renewableenergy/hydro-power/hydro-pumped-storage.
6. "History of Hydropower." Energy.gov,

https://www.energy.gov/eere/water/history-hydropower.
7. Smith, Norman. "The Origins of the Water Turbine." Scientific American, vol. 242, no. 1, 1980, pp. 138–49. JSTOR, http://www.jstor.org/stable/24966239. Accessed 21 Sep. 2022.
8. Fitzgerald, Dylan. "History." National Hydropower Association, 12 Sept. 2019, https://www.hydro.org/about/history/.
9. "Francis Turbine Cross Section." SaVRee, https://savree.com/en/encyclopedia/francis-turbine-cross-section.
10. Lewis1, B J, et al. "IOPscience." IOP Conference Series: Earth and Environmental Science, IOP Publishing, 1 Mar. 2014, https://iopscience.iop.org/article/10.1088/17551315/22/1/012020.
11. "Pumped Storage Hydropower." Energy.gov, https://www.energy.gov/eere/water/pumped-storage-hydropower.
12. John Roach • November 24, et al. "For Storing Electricity, Utilities Are Turning to Pumped Hydro." Yale E360, https://e360.yale.edu/features/for_storing_electricity_utilities_are_turning_to_pumped_hydro
13. U.S. Hydropower Market Report - Energy. https://www.energy.gov/sites/prod/files/2021/01/f82/us-hydropower-market-report-full- 2021.pdf.
14. "File: Hydroelectricdam.png - Energy Education." Energyeducation.ca, energyeducation.ca/wiki/index.php?title=File: Hydroelectricdam.png&oldid=4176. Accessed 18 Sept. 2022.
15. "Penstock." Wikipedia, 2 June 2020, en.wikipedia.org/wiki/Penstock.
16. Electricity Forum. "Hydroelectricity - Renewable Energy Generation Explained." Electricityforum.com, 2019, www.electricityforum.com/hydroelectricity.
17. "Hydro Turbine - Energy Education." Energyeducation.ca, energyeducation.ca/encyclopedia/Hydro_turbine.
18. Pamuła, Hanna. What Is Flow Rate? Volumetric and Mass Flow Rate. 12 Aug. 2022, www.omnicalculator.com/physics/flowrate#:~:text=Flow%20rate%20formulas%201%20Volumetric%20flow%20rate%20formula%3A,A%20×%20v%20where%20ρ%20%20Fluid%20density.
19. "File: Water Turbine with Generator.png - Energy Education." Energyeducation.ca, 28 Apr. 2020, Accessed 18 Sept. 2022.
20. Grover, Jasmine. Electromagnetic Induction: Laws, Formula and Applications. 5 Aug. 2022, collegedunia.com/exams/electromagnetic-induction-physics-articleid-408.
21. Bhatt, M. Siddhartha. Optimization of Annual Energy Generation in Run of the River of. Hydro Power Plants. The Journal OF CPRI. 8. 317-328, 1 Jan. 2013, Accessed 10 Sept. 2022.
22. Peake, Stephen. Renewable Energy: Powerfor a Sustainable Future. Oxford, Oxford. University Press, 2018, p. 344.
23. Peake, Stephen. Renewable Energy: Powerfor a Sustainable Future. Oxford, Oxford. University Press, 2018, p. 354.
24. Kunwor, Anil. Technical Specifications of Micro Hydropower System Design and Its. Implementation Feasibility Analysis and Design of Lamaya Khola Micro Hydro Power Plant. 2012, Accessed 18 Sept. 2022.
25. Team, Gecko Marketing. "What Is a Penstock and Its Role in Hydropower?" Blog.geckorobotics.com, 16 Feb. 2022, Accessed 18 Sept. 2022.
26. McMahon, Mary. "What Is a Penstock? (with Pictures)." About Mechanics, 1 Sept. 2022, www.aboutmechanics.com/what-is-a-penstock.htm. Accessed 17 Sept. 2022.
27. "Hydro Turbine - Energy Education." Energyeducation.ca, energyeducation.ca/encyclopedia/Hydro_turbine.
28. "Types of Hydropower Turbines." Energy.gov, 2019, www.energy.gov/eere/water/types-hydropower-turbines. Accessed 15 Sept. 2022.
29. Dincer Ibrahim, Haris Ishaq. "Renewable Hydrogen Production", Elsevier, 2021. ProQuest. Ebook Central, https://www.proquest.com/legacydocview/EBC/6817938?accountid=10267.
30. Daware, Kiran. Electrical Power Grid - Structure and Working. https://www.electricaleasy.com/2016/01/electrical-power-grid-structure-working.html. Accessed 8 Sept. 2022.
31. Francis Turbine: Working Principles, Diagram, Parts | Linquip. 13 Dec. 2020, https://www.linquip.com/blog/what-is-francis-turbine/.
32. "How Do You Connect Hydro to the Grid? - Renewables First." Renewables First - The. Hydro and Wind Company, https://www.renewablesfirst.co.uk/hydropower/hydropower- learning-centre/how-do-you-connect-hydro-to-the-grid/. Accessed 16 Sept. 2022.
33. Hydroelectric Power: How It Works | U.S. Geological Survey. https://www.usgs.gov/special-topics/water-science-school/science/hydroelectric-power- how-it-works. Accessed 16 Sept. 2022.
34. Sabhadiya, Jignesh. "What Is a Hydraulic Pump? - A Full Guide." Engineering Choice, 10. Jan. 2022, https://www.engineeringchoice.com/what-is-a-hydraulic-pump/.
35. Hydro, B. C. "How a Dam Works." BCHydro Power Smart for Schools, https://schools.bchydro.com/activities/electricity/how-a-dam-works. Accessed 19 Sept.2022.
36. Berga, Luis. "The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review." Engineering, vol. 2, no. 3, Sept. 2016, pp. 313–318, Accessed 21 Sept. 2022.
37. "Hydropower: Environmental Benefits." Army.mil, 2012, www.iwr.usace.army.mil/Missions/Value-to-the-Nation/Hydropower/Hydropower-

Environmental-Benefits/. Accessed 21 Sept. 2022.
38. “Power Generation and the Environment.” Google Books, 2013, Accessed 21 Sept. 2022.
39. “What Are the Environmental Impacts of Hydropower?” TRVST, 7 Aug. 2021, www.trvst.world/renewable-energy/environmental-impacts-of-hydropower/. Accessed 21 Sept. 2022.
40. “HydroPower and the World’s Energy Future” - International Hydropower Association https://www.ieahydro.org/media/ffab53b0/Hydropower%20and%20the%20World's%20Energy%20Future%20.pdf
41. Fitzgerald, Dylan. “Affordable.” National Hydropower Association, 12 Sept. 2019, https://www.hydro.org/waterpower/why-hydro/affordable/.
42. Rider, James A. “How Much Does It Cost to Build a Dam?” Howmuches, 5 Feb. 2022, https://howmuches.com/how-much-does-it-cost-to-build-a-dam/#:~:text=The%20average%20cost%20to%20construct%20a%20dam%20might,liters%20water%20capacity%20dam%20will%20cost%20around%20%2450%2C000.
43. Meyers, Glenn. “Hydropower Costs: Renewable Energy Hydroelectricity Costs vs Other. Renewable & Fossil Costs.” PlanetSave, 9 Mar. 2016, https://planetsave.com/2016/03/09/hydropower-costs-renewable-energy-hydroelectricity- costs-vs-renewable-fossil-costs/.
44. Katie Brigham. “Why Hydropower Is the Forgotten Giant of Clean Energy.” CNBC, CNBC, 2 June 2022, https://www.cnbc.com/2022/06/02/why-hydropower-is-the-worlds-most- overlooked-renewable.html.