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Review

From novel turbine designs to artificial intelligence: a review of cutting-edge innovations in hydropower systems

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A R T I C L E I N F O

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A B S T R A C T

This paper explores the breakthroughs made in hydropower technology and efficiency. The research aims to assess and highlight the advances in hydropower technology and efficiency by investigating the different breakthroughs such as improved turbine designs, aquatic life preservation in relation to the hydropower industry, the utilization of AI, simulations, and digitalization, advancements made in artificial channeling, exploring and advancing marine and hydrokinetic technologies, along with the methods used to optimize operations in the hydropower industry. Hydropower, as a clean and reliable renewable energy source, utilizes various types of structures to harness the kinetic energy of moving water to generate electricity. The main initiatives in advancing hydropower include increasing efficiency, improving cost effectiveness, exploring new technologies, and minimizing environmental impacts. Hydropower generates roughly six percent of the energy produced in the United States and roughly fifteen percent of all electricity worldwide. Over the last 20 years, global hydropower capacity has increased by seventy percent and is projected to grow by an additional seventeen percent between the years 2021 and 2030. This energy source shows a strong, steady upward trend in the advances made in hydropower technology and efficiencies.

1. Introduction

Hydropower was one of the first energy sources to be explored and utilized. This renewable energy source has been used for thousands of years. Early civilizations utilized this form of renewable energy to generate mechanical energy and complete tasks such as grinding grain [1]. The modern form of hydropower used to generate electricity began to gain traction in the late 1800's when the first hydroelectric power plant in the United States became operational in 1882 [2]. Over the last century, hydroelectric power has made many advances in design, technology, and efficiency. The conventional dam is one of the more commonly utilized hydroelectric power generation systems. The water collected in the man-made lake or reservoir flows through the intake valve and into a pipe also referred to as a penstock. The water then spins a turbine, which in turn spins a generator, ultimately producing electricity [3]. The conversion from water to wire is roughly 90% efficient. This is at the higher end of the spectrum as Coal, Natural gas, and Oil plants typically achieve roughly only 30% to 40% efficiency [4]. Once the energy is produced, it is fed into the electrical grid for distribution. Many of the largest hydropower dams are located in the western United States [5]. Roughly 60% of the state of Washington's electricity comes from hydropower. Currently, hydroelectric power is used in every state in the USA besides Delaware and Mississippi [6]. Hydropower has the potential to advance and improve environmental performance. With rising concerns for the environment and economic impacts, this energy source could potentially solve a multitude of global economic and environmental concerns. However, hydropower has its faults, such as negative environmental effects, including habitat loss, the effect on fish and wildlife, and the unnatural alterations made to the river flows, sediment deposition, water temperature, and water quality [7]. Potential advances focused on solving these environmental concerns could cause hydropower to become more desirable and mainstream. Economically, hydropower offers significant benefits such as reduced reliance on fossil fuels and low-cost electricity generation [8]. This outweighs the economic challenges that are associated with hydropower, such as the high initial cost of establishing a hydroelectric power plant and the environmental impacts that can potentially take place.

2. The different types of Hydropower plants

There are four main types of hydropower plants. The main types of hydropower facilities consist of Reservoir hydropower, Diversion Hydropower, Offshore hydropower, and pumped storage [9]. Each of these projects harnesses the energy of moving water in a different way. The type of hydropower facility implemented depends on factors such as water flow availability, type of water source available, and the potential amount of energy generated [10]. Hence, the use of offshore hydropower is often utilized along the coasts, while reservoir hydropower is implemented mainly along rivers or large bodies of water.

2.1 Pumped storage hydropower

Pumped Storage Hydropower (PSH) is the technique used to store energy by pumping water from a lower reservoir uphill to a higher reservoir during periods of low energy demand (Figure 1). Once the demand for energy increases, the water is released from the upper reservoir. As the water flows through turbines and moves towards the lower reservoir, it generates electricity [11]. An example of a low energy demand period would be when other renewable energy sources, such as wind and solar, are producing excess power or during the night [12]. The PSH system was first utilized in 1907 in Switzerland at the Engeweiher pumped storage facility [13]. The first pumped storage hydropower facility in the U.S., known as the Rocky River Plant, became operational in 1929 [14]. The PSH system helps create grid stability by storing energy during periods of low energy demand and ensuring a source of reliable power when the energy demand is high. PSH is the only technology for prolonged energy storage on the market and is known for its predictability and reliability [15]. Previously used PSH systems have been found to have negative environmental impacts, such as changes to ecosystems and water levels. One advancement made would be the design of the closed-loop PSH system. The closed-loop PSH is contained between two reservoirs but does not flow into or out of any natural bodies of water. This minimizes the effect on existing ecosystems and water levels in natural water bodies.

Another benefit of the closed-loop systems is that they can be located in areas that are not near rivers or lakes and utilize man-made sites such as mines that are no longer used and converted into reservoirs [16]. PSH technology has also undergone other advances such as new equipment controls, improved reversible pump-turbines, and adjustable speed turbines. These advances allow the pumping cycle to increase efficiency by 5% over the last 25 years [17]. PSH has several advantages in comparison to other forms of energy storage, including a low economic lifetime cost and a high power capacity [18].

2.2 Impoundment hydropower

Impoundment hydropower, which is also referred to as reservoir hydropower, is a type of hydropower plant that utilizes either a natural or man-made river. A dam is built to halt the flow of the river and create a reservoir of water. This allows the storage of water, which can then be released as needed to create a steady flow of generated electricity. When the water is released from the reservoir, it flows through a pipe also known as a penstock. The water flow causes the turbine blades to turn. The turbine is connected to a generator, which converts the mechanical energy of the turbine into electrical energy. The electrical energy generated can then be released into the electrical grid for distribution [20]. Impoundment hydropower allows for the storage of water for long periods of time, even when river levels begin to decrease. Impoundment hydropower plants allow control over the release of water, which allows operators to generate hydroelectricity on demand [21]. Disadvantages of reservoir hydropower facilities include the disruption of natural river flows, ecosystems, fish and wildlife populations, and water quality. Dams can also disrupt the natural formation of sediment, leading to poor water quality downstream and a potential negative impact on agricultural lands. Impoundment hydropower facilities require large areas of land, which can lead to land disputes [22]. Annually, reservoir hydropower plants generate roughly 4,000 terawatt-hours of electricity [23].

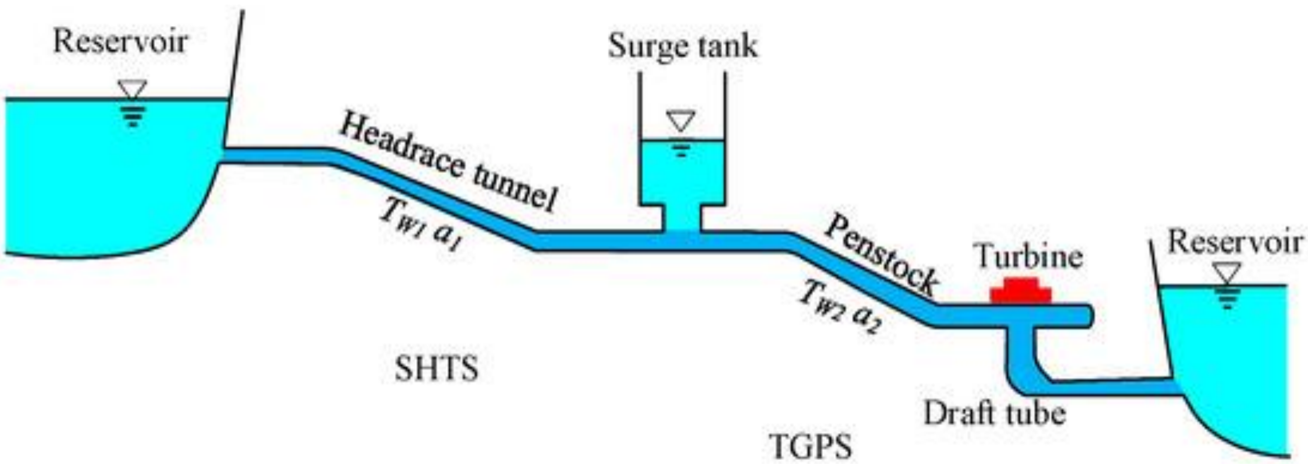

Figure 1. Pumped storage hydropower plant system [19]

A key advancement involving impoundment hydropower facilities would be the creation of a more efficient turbine design, which could be implemented in currently existing dams without the need to construct new dams. This would be a cost-efficient design advancement that would solve problems associated with impoundment facilities without the high costs of building a new dam site. The Natel's Restoration Hydro Turbine (RHT) is the first turbine in the hydropower industry that allows for the safe passage of fish and wildlife while still meeting high performance standards. This effort shows advances in efforts to preserve biodiversity while continuing the progression of renewable energy production [24]. In the United States alone, there are over 90,000 dams (Figure 2). The National Inventory of Dams (NID) states there are 92,075 dams currently in the United States. Only 3% or 2,500 of all dams in the U.S. actually generate power [25]. The non-powered dams (NPD) can be retrofitted to generate power. This would significantly increase the United States' hydropower capacity without the construction of any new dams [26].

2.3 Diversion hydropower

Diversion hydropower is a run-of-river (ROR) hydropower system that harnesses the electricity generation of a river's naturally occurring downward flow (Figure 3). Unlike an impoundment facility that flows directly through turbines, the ROR systems divert water into a channel or penstock to power turbines and generate electricity. The water is then returned to the river downstream, and the electricity produced is released into the grid for distribution [27]. This type of hydropower facility is convenient because it does not require a dam or reservoir to store water. Diversion hydropower offers minimal environmental impacts in comparison to other hydropower facilities by not disrupting the natural flow of rivers [28]. Run-of-river systems provide a great source of clean, renewable energy and have predictable seasonal outputs. This is convenient during the hotter seasons, where water levels may periodically deplete [29]. ROR systems are ideal only if there is a steadily flowing river or channel [30].

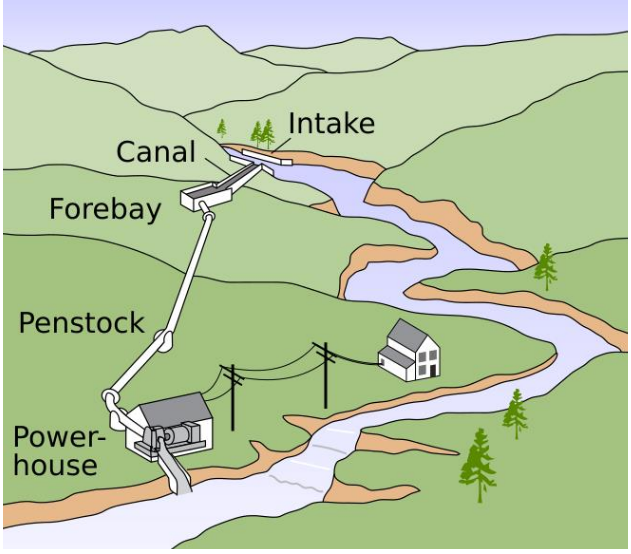

Figure 3. Run of river

2.4 Offshore hydropower

Offshore hydropower is a newly established method of harnessing waves and the power of tidal currents to produce hydroelectricity [31]. The largest body of water available in the world is the ocean. The two main types of offshore hydropower are tidal power and wave power [32]. Tidal power utilizes the constant and predictable fall and rise of tides to generate electricity [33]. Wave power relies on the potential energy produced from ocean waves [34]. Tidal barrages are structures commonly placed at the entrance of an estuary or bay. This allows water to be trapped in a reservoir during high tide and run through turbines to generate power as the tide recedes during the ebb current [35]. Tidal power is also harnessed through tidal stream turbines. This form of tidal power technology utilizes underwater turbines to harness the energy of tidal currents [36].

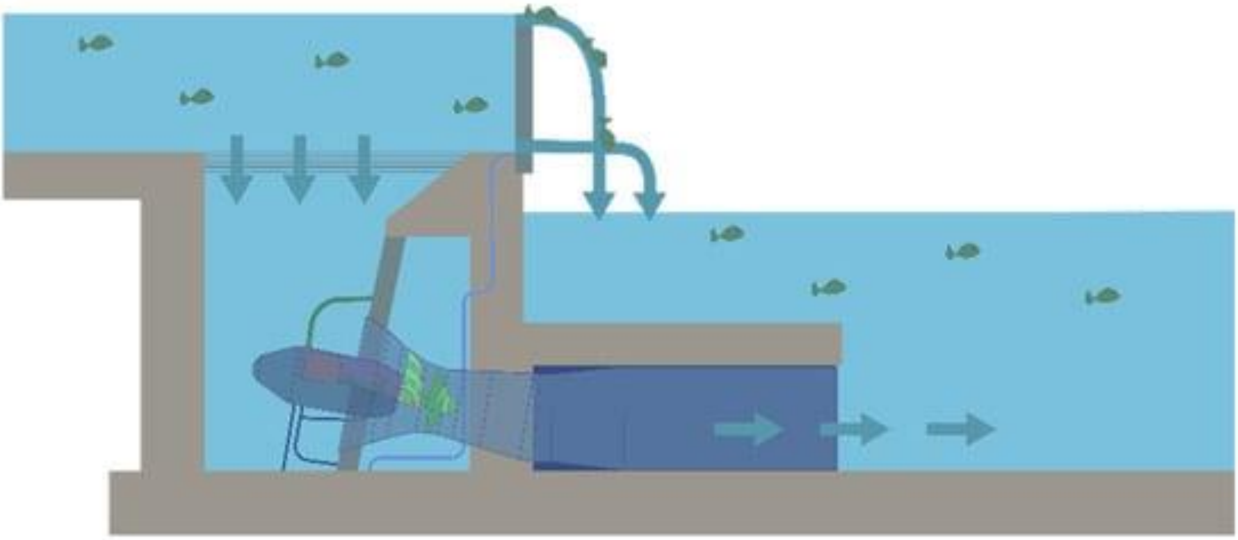

Figure 2. Hydroelectric dam diagram

The global tidal energy market is expected to grow at a compound annual growth rate (CAGR) of 12.5% from 2024 to 2030 [37]. Wave power is utilized by two main types of technology. The wave energy converters (WEC) are devices placed in the ocean near areas of high wave activity. The WEC devices often utilize specialized buoys or other devices to convert the kinetic energy of the waves into electricity [38]. Wave power can also be harnessed through offshore power plants. Offshore power plants allow for the utilization of the higher potential energy of waves while minimizing the environmental impacts that are associated with being near the shore [39]. Wave hydropower is still in the early stages of development, with many advances yet to be made. The International Panel on Climate Change (IPCC) estimates that the world's oceans could produce nearly 29,500 terawatt-hours of electricity annually from wave energy [40]. Since 2010, the cumulative global deployment for wave energy has reached 27 MW. 1.6 MW was deployed in 2023 alone [41]. Currently, offshore hydropower is more expensive than offshore wind power plants [42]. The U.S. Department of Energy's Water Power Technologies Office (WPTO) is funding research and projects to advance the commercial readiness of wave energy technologies through testing and system validation [43]. By utilizing the predictable wave and tidal cycles, we could substantially increase hydropower production and the utilization of renewable energy.

3. Advancements in Hydropower

The hydropower industry is advancing and growing yearly, nearly doubling its market value from $282.6 billion to $422.13 billion by 2025 [44]. Global electricity demand is a major factor in the growth of the hydropower market. Investing in hydropower is important, especially for developing countries, because it is a reliable and accessible renewable resource [45]. The traditional designs for hydropower facilities have not changed significantly since they were first introduced nearly two decades ago [46]. Due to cost concerns and environmental factors, it is not ideal to completely construct new hydropower plants. Therefore, upgrading and advancing already established facilities and technologies would increase efficiency and increase the appeal of hydropower. Issues faced within the hydropower industry that could potentially see advancements include measures that preserve aquatic life, improvements to turbine design, harnessing AI, and upgrades made to technology and hydropower plant sites already in place.

3.1 Aquatic life preservation

The main disadvantage of the hydropower industry is the negative impact that hydropower facilities have on aquatic wildlife. 22.3% of all fish that pass through hydropower turbines are killed or severely injured [47]. Natel Energy has teamed up with Pacific Northwest National Laboratory to design and test a new turbine design that allows for the safe passage of both small and large fish. The Natel's Restoration Hydro Turbine (RHT) is uniquely designed with thicker blades, rounded leading edges, and a forward slant from the blade's hub to tip. The research team tested the turbine's efficiency with the passage of rainbow trout, sturgeon, salmonids, alosines, and American eel. These fish ranged in size from 8-20 inches in length. More than 99% of fish passed through the turbine while still allowing for maximum performance output of energy [48]. Advancements are still being made to restore aquatic habitats, preserve endangered species, and improve dam operations. Statkraft, a leading global renewable energy producer in Europe, is working to rehabilitate the population of the endangered European eel. European eels are heavily affected due to the many hydropower plants and other man-made structures that disrupt their natural migration patterns to their spawning grounds. Statkraft has implemented plans to transport the eels upriver past hydropower plants in order to allow them a chance to breed and repopulate. This is an uncommon practice, but it is a step in conserving wildlife that is threatened by the construction of hydropower plants [49].

3.2 Improved turbine design

The most commonly used turbine design in hydropower plants is the Francis turbine (Figure 4). The Francis turbine is used mainly for larger-scale hydropower plants, while the Kaplan and Pelton turbines are used for specific head and flow conditions ranging from low to high [50].

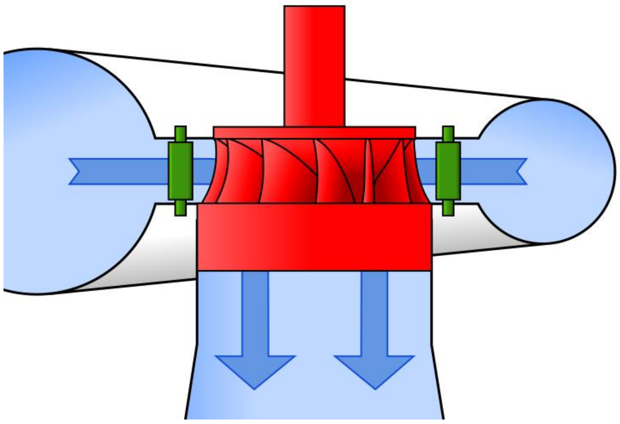

Figure 4. Francis turbine

Although these designs are efficient, there are still many improvements that can be made. As previously discussed, the RHT has been designed to preserve aquatic life that passes through the turbines. Hydropower plants have begun implementing the Novel turbine. The Novel turbine design allows for improved efficiency, reduced costs, and the implementation in areas not normally associated with hydropower generation, such as urban and offshore areas [51]. Novel turbines often differ from traditional turbine designs through the materials, geometries, or operation principles [52]. A popular example of a novel turbine being introduced is the Fin-ring turbine. The Fin-ring turbine consists of seven rings and 88 connecting cambered fins that optimize hydrodynamic performance [53]. Novel turbines provide a multitude of benefits that will help aid in the advancements and growth of hydropower. Statkraft has broken ground on the Hydroflex Project, which focuses on the development of turbine systems that can withstand fast-paced starts and stops. This focuses on the response time by allowing the turbine to run as needed and respond in real time to energy demands [54]. Research and implementation of turbines that focus on the speed of a turbine have also been introduced within the last decade. The Goldisthal PSH plant in

Germany was the first plant in Europe to utilize large variable speed turbines [55]. Variable speed technology allows for power regulation during pumping operations, improved efficiency, and optimized control of the power delivered into the grid [56]. A large variable-speed hydropower plant can go from idleness to maximum capacity in approximately 100 seconds [57].

3.3 Harnessing AI, simulations, and digitalization

Artificial intelligence (AI) technology has improved the hydropower industry's efficiency and accuracy [58]. AI has improved water management, operations, grid integration, and allows facilities to accurately predict when maintenance on turbines, generators, and other machinery is required [59]. The Wuqiangxi hydropower plant in Hunan province, China, has implemented AI-based technology to inspect it. The Hydropower Smart Remote O&M System utilizes a fleet of drones and robots to collect data using sound and image recognition tools and infrared thermometers, among other devices. This system allows for repairs and maintenance to be made as needed and not solely during scheduled inspections completed by plant personnel [60]. Simulations allow researchers focused on advancing the hydropower industry to develop, design, and test potential designs for hydropower technology without the cost of fabricating and testing an actual prototype [61]. The National Renewable Energy Laboratory (NREL) has developed the ARIES platform, which creates a controlled, real-world environment that allows researchers to emulate and evaluate prototype controls and advance hydropower technologies [62]. NREL is also developing a platform called the Real-Time Hydropower Emulation Platform, which mimics hydropower facilities in real time, allowing researchers to test technologies and controls and minimize the risks involved [63]. Hydropower digitalization has become a turning point in the advancement of hydropower technologies and efficiencies. Digitalization is the process of incorporating digital technologies into various aspects of operations to increase efficiency and lead to advancements [64]. Hydropower digitalization has created platform solutions to aid in areas such as digital simulation, predictive maintenance, water monitoring, and asset management [65].

3.4 Marine and hydrokinetic technology

Marine energy utilizes the kinetic energy created during the movement of water [66]. It focuses on natural occurrences such as waves, tides, and ocean currents [67]. This differs from traditional hydropower, which relies on facilities such as dams and impoundments to generate electricity. The five main types of ocean energy technologies are tidal stream, ocean waves, river hydrokinetic, ocean thermal, and ocean current [68]. Marine and hydrokinetic (MHK) technologies were developed to aid in harnessing marine energy [69]. MHK technologies include tidal stream generators (Figure 5), barrage systems, and instream hydrokinetic devices [70]. These systems allow for the generation of clean energy, are a reliable energy source, and are considered cost-effective due to relying on naturally replenishing energy sources [71]. This is a promising and reliable future option for areas that are remote or off-grid [72]. Research and development for marine and hydrokinetic technology are advancing and focused on the improvement of MHK technologies' efficiency, durability, and cost-effectiveness [73].

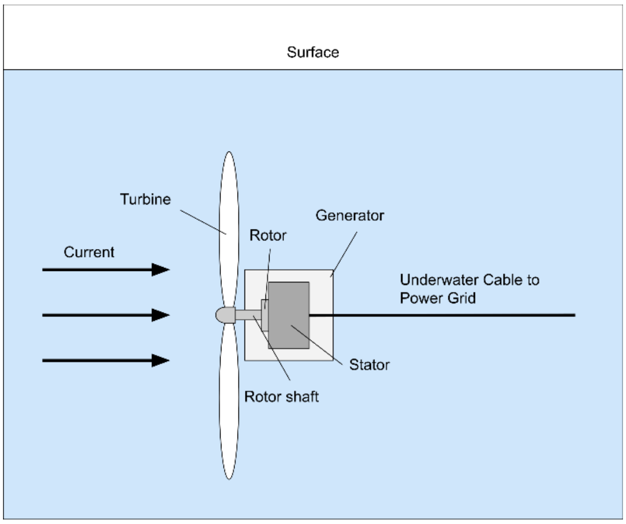

Figure 5. Diagram of tidal stream power generation

3.5 Artificial Channeling

Advancements in artificial channeling focus on improving efficiency, cost effectiveness, and the environmental concerns caused. Artificial channeling is an advancement in the hydropower industry that works closely with MHK technology [74]. To harness marine energy, barrage systems, instream hydrokinetic devices, and tidal stream generators are implemented [75]. A barrage system works similarly to a dam by creating a controlled water flow by utilizing the difference in water levels that naturally occur as the tide levels alternate from low to high. As the water levels rise, the barrage gates open, allowing the water to pool into a water basin. As the tide recedes, the collected water is released through the sluice gates as it flows through a turbine, generating electricity [76]. Instream hydrokinetic devices and tidal stream generators are both MHK technologies that harvest power from the currents [77]. The innovation of novel turbine designs, such as fish-friendly turbines, hydrokinetic turbines, and vortex turbines, has improved both the efficiency and environmental impacts of artificial channeling [78]. Fish-friendly turbines allow for fish to safely pass through turbines [79]. Vortex turbines and hydrokinetic turbines are a potential breakthrough in harnessing power in areas with limited water flow or low-speed flows captured in artificial channels such as canals [80]. This is ideal for areas where traditional hydropower is not suitable (Figure 6).

3.6 Repairing and advancing outdated hydropower plant sites

While advancing the hydropower industry is of utmost importance, preserving and maintaining the hydropower plant sites already in use is crucial. The annual operations and maintenance (O&M) cost for hydropower plants can range from 1.5% to 2.5% of the initial investment. For a major hydropower plant, this converts to roughly 15 to 30 million dollars [81]. Smaller plants have lower operation and maintenance costs. Hydropower plants have a lifespan of 50 to 100 years, but often exceed that when properly maintained [82]. Advancing outdated hydropower plants involves upgrading technologies, improving infrastructure, replacing or repairing aging components, and integrating new technologies that could potentially optimize operations. The modernization of hydropower facilities can have a multitude of benefits, including potentially cost savings due to lower maintenance requirements, extending plant lifespans, and improved energy security.

Figure 6. A barrage hydroelectric power plant

4. Conclusion

Hydropower is a promising renewable energy source that is steadily improving and evolving. The main goal in advancing hydropower is to increase efficiency, improve cost effectiveness, explore new technologies, and minimize environmental impacts. As covered in this paper, prominent renewable energy companies such as Natel and Statkraft, amongst others, have made headway in advancing the hydropower industry and overall promoting the use of hydropower. Over the last two decades, global hydropower capacity has increased by 70% and is projected to grow by an additional 17% between the years 2021 and 2030. With hydropower on the rise, the possibilities of novel designs and technology in the hydropower industry are on the horizon.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The author declares no potential conflict of interest.

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