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A preliminary Study on Pump Storage Hydro-Electric Power (PSHP) and its Potentials in Sustainable Energy Development in the 21st Century

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Abstract

The growing demand for a reliable energy storage solution have become increasingly important due to the world's expanding energy consumption and increasing pressure for a transition to low-carbon and sustainable energy technologies. One of the most advanced, effective, and extensive energy storage technologies on the market right now is Pump Storage Hydro-Electric Power (PSHP). This research study offers a preliminary analysis of PSHP's contribution to 21st-century sustainable energy development, looking at its technological underpinnings, present worldwide implementation, and potential. The study also underscores how PSHP's grid stability, load balancing, and energy storage capabilities offering a seamless integration of intermittent renewable energy sources. The results from this study indicate that PSHP continues to be a vital accelerator of sustainable energy transitions in spite of current obstacles, especially in areas with a high penetration of renewable energy sources. Thus, to increase PSHP implementation and ensure that it is in line with both the demands of energy security and global climate goals, policy proposals and future research initiatives are put forth in this research. This present research study supports the PSHP's critical position in a decarbonized energy future and advances to the continuing conversation on sustainable energy storage technologies.

Keywords: Pump storage hydro-electric power, Renewable energy integration, Energy storage.

1 | Introduction

The demand for electricity in Nigeria has been steadily increasing over the years due to population growth, urbanization, and industrialization. However, the country's electricity supply has been unable to keep up with this growing demand, leading to frequent power outages and blackouts [1], [2]. In order to address this issue

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and enhance the electricity supply in Nigeria, the implementation of Pump Storage Hydro (PSH) electric power models has been proposed as a viable solution. PSH electric power systems have long been recognized as an effective means of enhancing electricity supply [3], [4]. These systems utilize the principle of storing excess electricity during periods of low demand by pumping water from a lower reservoir to a higher one, and then releasing the stored water to generate electricity during peak demand periods [5], [6]. The system model has proven to be a reliable and efficient method of balancing the grid and ensuring a stable supply of electricity. One of the key potentials of PSH systems is their ability to provide rapid response to fluctuations in electricity demand. Unlike other forms of renewable energy such as solar or wind power, which are dependent on weather conditions, PSH systems can be quickly ramped up or down to meet changing demand levels [7]. This flexibility makes them an ideal complement to intermittent sources of energy, helping to ensure a reliable and stable electricity supply. Furthermore, PSH systems have a high energy efficiency, with some systems achieving efficiencies of up to 80%. This is due to the fact that the same water can be used multiple times to generate electricity, resulting in minimal energy loss [8], [9]. In addition, PSH systems have a long lifespan, with some facilities operating for over 50 years with minimal maintenance requirements. This makes them a cost-effective option for enhancing electricity supply over the long term. PSH systems can provide grid stability and support the integration of renewable energy sources. As the share of renewable energy in the electricity mix continues to grow, the need for flexible and reliable energy storage solutions becomes increasingly important [10]. PSH systems can help to smooth out fluctuations in renewable energy generation, ensuring a stable and secure electricity supply.

The history of Pump Storage Hydro-Electric Power (PSHP) dates back to the late 19th century, with the first commercial plant being built in Switzerland in 1909. Since then, this technology has been widely adopted around the world, with numerous plants in operation in countries such as the United States, Japan, India and China [11], [12]. These plants have proven to be highly effective in enhancing electricity supply, providing a reliable source of energy that can be quickly dispatched to meet peak demand. Innovations in PSHP have led to advancements in efficiency and capacity. Modern plants are equipped with state-of-the-art turbines and control systems that allow for more precise operation and greater flexibility in responding to changes in demand [13], [14]. Additionally, advancements in materials and construction techniques have enabled the development of larger and more powerful plants, further increasing their contribution to electricity supply enhancement. Looking towards the future, PSHP is expected to play an even greater role in the transition to a more sustainable energy system. As renewable energy sources such as wind and solar become more prevalent, the need for energy storage solutions will only grow [15]. PSHP offers a proven and reliable option for storing excess energy and balancing the grid, making it an essential component of a modern electricity supply system. The provision of an alternative power supply becomes crucial when there is a lack of electricity from the national grid. Airobaman et al. [16] emphasize the importance of developing a pump model that utilizes HOMER Technology to enhance the electric power supply.

In the pursuit of improving the effectiveness of such pump models, Gevorkov and Kirpichnikova [17] emphasize the significance of examining the properties of Photovoltaic (PV) water pumping systems. Understanding these properties contributes to the overall performance of the model. To optimize the regulator's parameters of the Alternate Source Power Supply Unit (ASPSU), Pan et al. [18] propose the use of a stability-degree criteria in the particle swarm optimization algorithm. This optimization approach plays a crucial role in enhancing the stability and efficiency of the system. Electricity outages in urban households, particularly in developing countries like Accra, Ghana, present significant challenges [19]. Addressing these issues is of utmost importance to ensure a reliable and consistent power supply [20]. Highlights the value of a broad set of result scenarios, which serves as a reference for stakeholders involved in decision-making processes. Pumped-storage hydropower technology is identified as a promising solution for improving power supply reliability, especially in uncertain conditions [21]. By utilizing pumped hydro storage, the system would achieve greater reliability and stability. In the context of water distribution systems, the integration of small pumped-storage hydropower units offers an optimization framework to minimize operating costs associated with power and water consumption [22]. This integration strategy was essential for efficient and cost-effective operation. An increase in grid failure frequency and mean repair time would result in higher total operating costs [23]. However, Shirinda et al. [24] propose an optimal energy management model that combines a grid-connected solar PV system with Underground Pumped Hydro Storage (UPHS) to mitigate grid consumption costs, particularly during high-demand winter seasons. Finally, as the penetration of PV systems increases, there is a growing concern regarding the deterioration of power supply reliability [25]. Therefore, it is imperative to develop strategies to address and mitigate this issue.

2 | History of Pump Storage Hydroelectric Power System

The PSHPS has a long and rich history dating back to the late 19th century. This innovative technology has played a crucial role in the development of the modern energy grid, providing a reliable and efficient source of electricity storage and generation [26]. The historical chronicles and trends of PSHPS, its evolution over the years and its significance in the energy sector are stated in this section. The concept of PSHPS can be traced back to the late 19th century, with the first commercial installation being built in Switzerland in 1909. This early system utilized the natural flow of water to generate electricity, with excess power being used to pump water back up to a higher reservoir for storage. This innovative approach allowed for the efficient storage and utilization of energy, paving the way for the development of modern PSHPS [27]. Over the years, PSHPSs have evolved significantly, with advancements in technology and engineering leading to increased efficiency and capacity. Today, these systems are capable of storing large amounts of energy and providing a reliable source of electricity during peak demand periods. This has made PSHPSs an essential component of the energy grid, helping to stabilize the grid and ensure a consistent supply of electricity [28]. In recent years, there has been a growing trend towards the development of PSHPSs as a means of integrating renewable energy sources into the grid. With the increasing penetration of solar and wind power, there is a need for reliable energy storage solutions to balance out the intermittent nature of these sources. PSHPSs have emerged as a viable option for storing excess renewable energy and providing a stable source of electricity when needed [29], [30]. The historical chronicles and trends of PSHPS highlight its importance in the energy sector and its role in shaping the modern energy grid. With advancements in technology and a growing focus on renewable energy, PSHPSs are poised to play an even greater role in the future. As we continue to transition towards a more sustainable energy system, PSHPSs will be a key component in ensuring a reliable and efficient energy supply.

3 | Advancements in Pump Storage Hydroelectric Power System

PSHPSs have been a key player in the renewable energy sector for decades, providing a reliable and efficient way to store and generate electricity. Recent advancements in this technology have further improved its capabilities, making it an even more attractive option for meeting the growing energy demands of the modern world. Some of the key milestones in the development of pump storage hydroelectric power systems are outlined below:

I. The increased efficiency of the technology: Advances in turbine design and control systems have allowed for higher conversion efficiencies, resulting in more electricity being generated from the same amount of water. This increased efficiency has made pump storage systems more cost-effective and competitive with other forms of energy generation [31], [32].

II. The development of new materials and construction techniques that have allowed for the construction of larger and more powerful facilities: These advancements have enabled the development of mega-scale pump storage projects, such as the recently completed 3,000 MW Fengning Pumped Storage Power Station in China. These large-scale projects have the potential to provide significant amounts of clean, renewable energy to the grid, helping to reduce reliance on fossil fuels and lower greenhouse gas emissions [33], [34].

III. Increase in the flexibility and reliability of these systems: New control systems and grid integration technologies have been developed to allow pump storage facilities to respond quickly to changes in demand and help stabilize the grid during periods of high variability in renewable energy generation. These advancements have made pump storage systems an essential component of a modern, reliable energy grid [35], [36].

Overall, the recent advancements in PSHPSs have significantly improved the capabilities and potential of this technology. With increased efficiency, larger scale projects, and improved flexibility and reliability, pump storage systems are poised to play a key role in the transition to a more sustainable energy future. As the world continues to seek out clean and renewable sources of energy, PSHPSs will undoubtedly be a critical part of the solution.

4 | Implementation Process of Pump Storage Hydroelectric Power System

The PSHP systems are a type of energy storage system that utilizes the gravitational potential energy of water to generate electricity. This system consists of two reservoirs located at different elevations, connected by a series of pipes and pumps [37]. During periods of low electricity demand, excess electricity is used to pump water from the lower reservoir to the upper reservoir. When electricity demand is high, water is released from the upper reservoir to the lower reservoir, passing through turbines that generate electricity. The construction of a process pump storage hydroelectric power system involves several detailed steps.

I. Site selection: Site selection process where suitable locations with adequate water supply and elevation differences are identified. Once a site is selected, the next step is to obtain the necessary permits and approvals from regulatory authorities.

II. Excavation of the upper and lower reservoirs: The upper reservoir is typically located at a higher elevation to maximize the potential energy of the water. The reservoirs are lined with impermeable materials to prevent water leakage.

III. The intake structure is constructed at the lower reservoir to allow water to flow into the system: This structure includes screens to prevent debris from entering the system. The outlet structure is built at the upper reservoir to control the release of water.

IV. The installation of the pipes and pumps that connect the two reservoirs: These pipes are typically made of durable materials such as steel or concrete to withstand the high pressures and flow rates of the water. The pumps are used to lift water from the lower reservoir to the upper reservoir during off-peak hours.

V. The installation of turbines and generators at the lower reservoir: These components are essential for converting the potential energy of the water into electricity. The turbines are connected to the generators, which produce electricity that is fed into the grid.

VI. Installation of control systems and monitoring equipment to ensure the efficient operation of the system: These systems regulate the flow of water between the reservoirs and optimize the generation of electricity based on demand.

The construction of a process PSHPS is a complex and detailed process that requires careful planning and execution. By following the steps outlined above, developers can build a reliable and efficient energy storage system that can help meet the growing demand for renewable energy sources.

5 | Factors that Affects the Implementation of Pumped Storage Hydroelectric System

PSHPSs are a crucial component of the renewable energy landscape, providing a reliable and efficient way to store and generate electricity. However, the successful implementation of these systems can be influenced by a variety of factors, which are highlighted as follows:

I. The availability of suitable sites for construction: Pump storage systems require specific geographic features, such as a large body of water at a higher elevation than the lower reservoir, in order to function effectively. Finding suitable sites that meet these criteria can be a challenge, particularly in densely populated areas where land is scarce [38], [39].

II. The cost of construction and operation: Building a pump storage system can be a significant investment, requiring substantial financial resources. Additionally, the ongoing costs of operating and maintaining the system can be substantial. These costs can be a barrier to implementation, particularly in regions where funding for renewable energy projects is limited [40], [41].

III. Regulatory and permitting requirements: Obtaining the necessary approvals and permits to construct and operate a pump storage system can be a complex and time-consuming process. Delays in the permitting process can increase costs and hinder the timely implementation of the system [42], [43].

IV. The availability of skilled labor and technical expertise: Building and operating a pump storage system requires specialized knowledge and skills, and finding qualified personnel to design, construct, and maintain the system can be a challenge. In regions where there is a shortage of skilled labor in the renewable energy sector, implementing pump storage systems can be more difficult [44].

The successful implementation of PSHPSs can be influenced by a variety of factors, including the availability of suitable sites, the cost of construction and operation, regulatory and permitting requirements, and the availability of skilled labor and technical expertise. Addressing these factors is essential to ensuring the widespread adoption of pump storage systems as a reliable and efficient source of renewable energy.

6 | Factors that Affects the Smooth Performance and Functionality of Existing Pumped Storage Hydroelectric Systems

PSHPSs play a crucial role in balancing the supply and demand of electricity, especially during peak periods. However, there are several factors that can affect the smooth performance and functionality of existing PSHPSs, which are:

I. The availability of water: PSHPSs rely on the availability of water to generate electricity. If there is a shortage of water, either due to drought or other factors, the system may not be able to operate at full capacity. This can lead to a decrease in the overall efficiency of the system and can impact the reliability of the electricity supply [45].

II. The condition of the equipment: Like any other mechanical system, the components of these systems can wear out over time. If the equipment is not properly maintained, it can lead to breakdowns and downtime, which can impact the overall performance of the system [46].

III. External factors such as extreme weather events: For example, severe storms or flooding can damage the infrastructure of the system, leading to disruptions in the electricity supply. It is important for operators of these systems to have contingency plans in place to deal with such events and minimize their impact on the system [47], [48].

Overall, there are several factors that can affect the smooth performance and functionality of existing PSHPSs. It is important for operators to be aware of these factors and take proactive measures to address them in order to ensure the reliable operation of these systems. By doing so, they can help to maintain a stable and efficient electricity supply for consumers.

7 | Types of Pumped Storage Hydroelectric Systems

Pump storage hydroelectric power systems are a type of renewable energy technology that utilizes the gravitational potential energy of water to generate electricity. These systems are characterized by their ability to store and release energy quickly, making them ideal for balancing the fluctuations in supply and demand on the electrical grid [10]. There are several types and classifications of PSHPS, each with its own unique characteristics and advantages. Some of the most common types of PSHPSs are:

I. The conventional closed-loop system: In this system, water is pumped from a lower reservoir to an upper reservoir during periods of low electricity demand, and then released back down to the lower reservoir through turbines to generate electricity during periods of high demand (see *Fig. 1*). This type of system is highly efficient and can respond quickly to changes in demand, making it a popular choice for grid stabilization [49], [50].

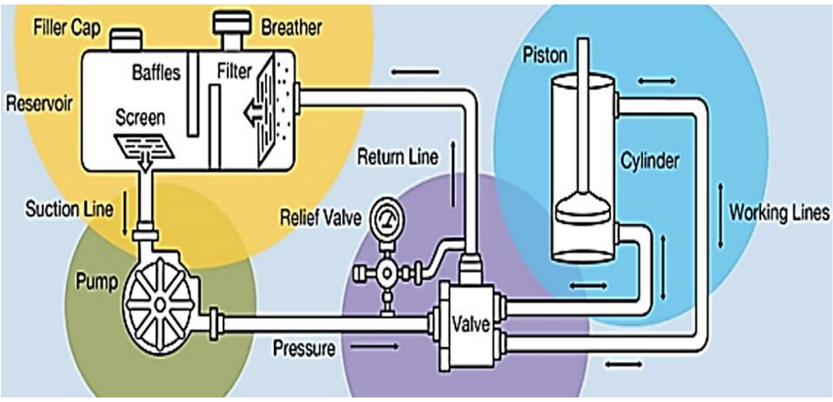

Fig. 1. Closed loop systems [51].

II. The open-loop system: The open loop system uses natural bodies of water as the upper and lower reservoirs as shown in *Fig. 2*. In this system, water is pumped from a lower body of water to an upper body of water during off-peak hours, and then released back down through turbines to generate electricity during peak hours. While open-loop systems can be more cost-effective to build than closed-loop systems, they are also more susceptible to environmental concerns such as water quality and aquatic habitat disruption [51], [52].

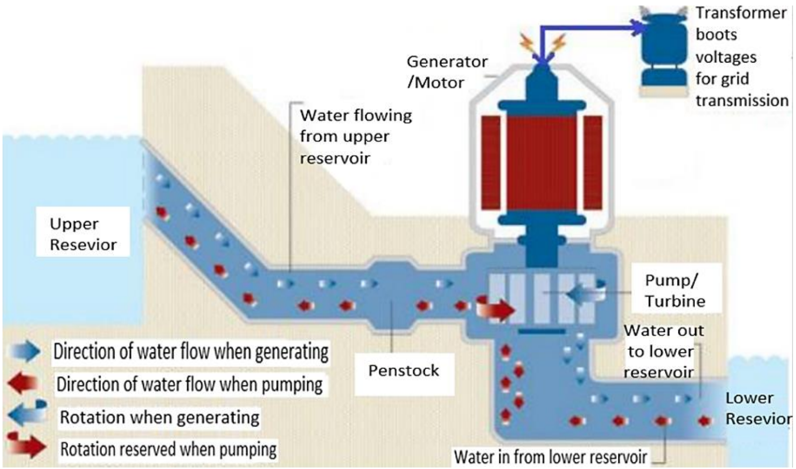

Fig. 2. The open-loop system [52].

III. The variable-speed system: As illustrated in *Fig. 3*, the Variable-Speed Pump Storage (VSPS) system uses variable-speed pumps and turbines to optimize energy efficiency. By adjusting the speed of the pumps and turbines based on the current demand for electricity, variable-speed systems can operate more efficiently than traditional fixed-speed systems. This type of system is particularly well-suited for grid stabilization in regions with fluctuating electricity demand [53], [54].

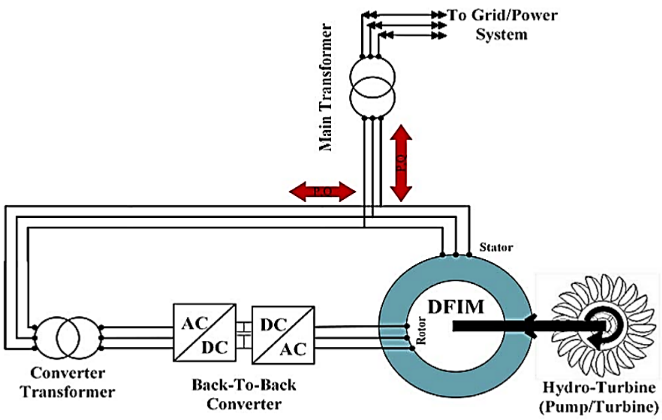

Fig. 3. Variable speed pumped storage system [55].

IV. In addition to these main types of PSHPSs, there are also several other classifications based on factors such as size, location, and design. For example, some pump storage systems are classified as standalone facilities, while others are integrated into existing hydroelectric power plants. Similarly, some systems are located in mountainous regions with natural elevation differences, while others are built using artificial reservoirs and tunnels to create the necessary height differential [56].

Overall, PSHPSs are a versatile and efficient technology for generating electricity from renewable sources. By understanding the various types and classifications of these systems, policymakers and energy planners can make informed decisions about the best options for grid stabilization and renewable energy integration. As the demand for clean and sustainable energy continues to grow, PSHPSs will play an increasingly important role in meeting our energy needs.

8 | Components of Pump Storage Hydroelectric Power Systems

A PSHPSs is a complex and efficient method of generating electricity that involves several key components working together seamlessly [15]. This system is designed to store and generate electricity during periods of low demand, and then release it during peak demand times. The various components involved in a PSHPS and their importance in the overall functioning of the system includes the upper reservoir, lower reservoir, penstock, turbines, pumps, and generators. The upper reservoir is where water is stored at a higher elevation, while the lower reservoir is where water is stored at a lower elevation [57]. The penstock is a large pipe that connects the two reservoirs and allows water to flow between them. The turbines are used to convert the energy of flowing water into mechanical energy, which is then used to drive the pumps or generators. The pumps are used to pump water from the lower reservoir to the upper reservoir when electricity is abundant, while the generators are used to convert the mechanical energy produced by the turbines into electrical energy [58]. Some of the key components in a PSHPS are:

I. The pump itself: The pump is responsible for transferring water from a lower reservoir to an upper reservoir during periods of low electricity demand. The efficiency and reliability of the pump are critical to the overall performance of the system. A well-designed pump can help minimize energy losses and maximize the amount of electricity that can be generated during peak demand periods [59], [60].

II. The turbine: The turbine is responsible for converting the potential energy of the stored water into mechanical energy, which is then used to generate electricity. The design of the turbine can have a significant impact on the overall efficiency and performance of the system. A well-designed turbine can help maximize the amount of electricity that can be generated from the stored water, while also minimizing energy losses [61], [62].

III. Penstocks: Penstocks are a crucial component in the design of PSHPSs. S illustrated in *Fig. 4*, these systems are used to store and generate electricity by pumping water from a lower reservoir to a higher reservoir during periods of low electricity demand, and then releasing the water back down through turbines to generate electricity during periods of high demand [63], [64]. Penstocks are large pipes or channels that transport water from the reservoir to the turbines, and are an important consideration in the design of these systems for several reasons.

IV. Penstocks play a critical role in the efficiency of PSHPSs: The size, material, and design of the penstock can have a significant impact on the flow rate and pressure of the water being transported to the turbines. A well-designed penstock will minimize friction losses and ensure that the maximum amount of water reaches the turbines, resulting in higher energy output and overall system efficiency [11], [65].

V. Penstocks are also important for the safety and reliability of PSHPSs. The pressure of the water flowing through the penstock can be extremely high, and any leaks or failures in the penstock can result in catastrophic damage to the system and surrounding environment. Therefore, it is essential that penstocks are designed and constructed to withstand these high pressures and ensure the safe and reliable operation of the system [66], [67].

VI. The location and layout of penstocks within the PSHPSs are also important considerations. Penstocks must be strategically placed to minimize energy losses and optimize the flow of water to the turbines [68], [69].

VII. The length and slope of the penstock can impact the overall efficiency and performance of the system, making it crucial to carefully consider these factors during the design phase [70], [71].

Penstocks are a critical component in the design of PSHPSs, playing a key role in the efficiency, safety, and reliability of these systems. By carefully considering the size, material, design, and layout of penstocks, engineers can optimize the performance of PSHPSs and ensure the sustainable generation of electricity.

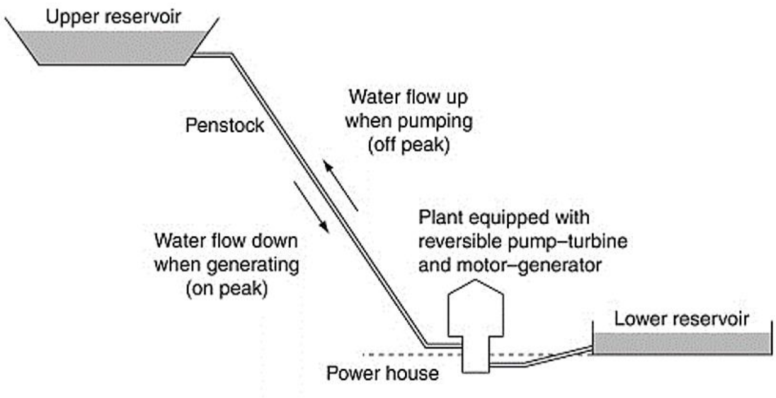

Fig. 4. Illustration of a storage hydroelectricity power plant [72].

9 | Design Process of PSHPSs

PSHPSs are a crucial component of the renewable energy landscape, providing a reliable and efficient way to store and generate electricity. The design process for these systems is complex and requires careful planning and consideration of various factors [72]. The step by step procedure in designing process PSHPSs are as follows:

I. To conduct a thorough site assessment: This involves evaluating the topography of the site, the availability of water sources, and the proximity to existing infrastructure such as transmission lines. The site assessment will help determine the feasibility of the project and identify any potential challenges that may need to be addressed during the design process [73].

II. Develop a detailed design plan: This plan should include the layout of the power plant, the size and capacity of the turbines and pumps, and the configuration of the reservoirs. The design plan should also take into account factors such as environmental impact, safety regulations, and cost considerations [74].

III. Procure the necessary equipment and materials for the project: This may involve working with suppliers to source turbines, pumps, and other components, as well as hiring contractors to assist with construction and installation. It is important to carefully vet suppliers and contractors to ensure that they have the necessary expertise and experience to complete the project successfully [75].

IV. Begin construction of the PSHPSs: This may involve excavating the site, building the reservoirs, installing the turbines and pumps, and connecting the system to the grid. Throughout the construction process, it is important to adhere to safety regulations and quality standards to ensure the reliability and efficiency of the system [59].

V. Commission the PSHPSs: This involves testing the system to ensure that it is operating correctly and efficiently, as well as training operators on how to manage and maintain the system. Once the system is commissioned, it can begin generating electricity and providing a reliable source of renewable energy [76].

Designing a PSHPSs is a complex and multifaceted process that requires careful planning and consideration of various factors. By following a comprehensive step-by-step design process, project developers can ensure the successful implementation of a PSHPS that provides a reliable and efficient source of renewable energy.

10 | Control and Monitoring Systems as Important Design Criteria for PSHPS

Control and monitoring systems are crucial design criteria for PSHPSs. These systems play a vital role in ensuring the efficient operation and performance of the power plant [77]. Some of the key reasons why control and monitoring systems are important in PSHPSs are highlighted as follows:

I. Its ability to optimize the performance of the plant: These systems allow operators to monitor various parameters such as water levels, flow rates, and power output, and make real-time adjustments to ensure that the plant is operating at its maximum efficiency. By continuously monitoring and controlling these parameters, operators can minimize energy losses and maximize the overall output of the power plant [78], [79].

II. It is essential for ensuring the safety and reliability of PSHPSs: These systems provide operators with real-time information on the condition of the plant, allowing them to quickly identify and address any potential issues before they escalate into major problems. By having a comprehensive monitoring system in place, operators can prevent equipment failures, reduce downtime, and ensure the continuous operation of the power plant [80], [81].

III. It is important for optimizing the economic performance of PSHPSs: By continuously monitoring and controlling the operation of the plant, operators can identify opportunities to reduce operating costs, increase revenue, and improve overall profitability. For example, by adjusting the operation of the plant based on real-time market conditions, operators can take advantage of peak demand periods and maximize the revenue generated by the power plant.

Control and monitoring systems are essential design criteria for PSHPSs. These systems play a crucial role in optimizing the performance, ensuring the safety and reliability, and maximizing the economic performance of these facilities. By investing in high-quality control and monitoring systems, operators can ensure the successful operation of pump storage hydroelectric power systems and maximize their overall benefits [82].

11 | Criteria that should be considered for Designing PSHPSs

PSHPSs are a crucial component of the renewable energy landscape, providing a reliable and efficient way to store and generate electricity. When designing such systems, there are several key considerations that must be taken into account to ensure optimal performance and efficiency. The list of various criteria that should be considered when designing PSHPSs are as follows:

I. The site selection: The location of the system will have a significant impact on its overall efficiency and performance. Factors such as the availability of water sources, topography, and proximity to existing infrastructure must be carefully evaluated to determine the most suitable site for the system [83].

II. The size and capacity of the system: The size of the system will depend on factors such as the expected energy demand, available land area, and budget constraints. It is important to carefully assess these factors to determine the optimal size and capacity of the system to meet the energy needs of the area [84].

III. The availability of suitable topography: The site must have a sufficient elevation difference between the upper and lower reservoirs in order to generate the necessary head for the system to operate effectively [85].

IV. The site must have a suitable geological composition: This is to support the construction of the reservoirs and other infrastructure required for the system [86].

V. The proximity to water sources: PSHPSs require a large amount of water to operate, so it is important to select a site that has access to a reliable and abundant water source. This can include rivers, lakes, or other bodies of water that can be used to fill the reservoirs and generate power [87].

VI. The proximity to existing electrical infrastructure: This is also an important factor when citing a PSHPSs. These systems require a connection to the electrical grid in order to distribute the electricity they generate. Locating a pump storage facility near existing transmission lines can help reduce the cost and complexity of connecting the system to the grid [88].

VII. The type of reservoir used in a PSHPS: The size and location of the reservoir can have a significant impact on the overall efficiency of the system. For example, a reservoir located at a higher elevation will have a greater potential energy storage capacity than a reservoir located at a lower elevation. Additionally, the type of reservoir used can also impact the environmental impact of the system, as well as the cost of construction and operation [89].

VIII. Environmental considerations: This must also be taken into account when designing PSHPSs. The impact of the system on the surrounding ecosystem, including wildlife habitats and water quality, must be carefully evaluated to minimize any negative effects on the environment [90].

IX. The size of the pump storage system: A larger system can potentially generate more power and provide greater benefits in terms of energy storage and grid stability. However, larger systems also require more land area and resources, which can increase the cost and complexity of the project. Therefore, it is important to carefully weigh the benefits and drawbacks of different system sizes in order to determine the most appropriate size for a specific project [91].

Designing PSHPSs requires careful consideration of a variety of factors to ensure optimal performance and efficiency. When designing PSHPSs, there are several important considerations and criteria that must be taken into account in order to ensure the success and efficiency of the system. The size of the system will depend on a variety of factors, including the power output required, the available land area, component selection, environmental impact, and the budget for the project. It is important to carefully consider these factors in order to determine the optimal size for the system.

12 | Conclusion

PSHP remains one of the prime movers of sustainable energy development in the 21st century which offers an efficient and a scalable solution for energy storage and grid stability. As the world accelerates its transition toward renewable energy, PSHP plays a significant and resilient electricity supply value chain. Despite challenges ranging from high initial costs, geographical limitations, and environmental concerns, technological advancements, there is a common synergy that PSHP offers sustainable development platform for clean energy matrix. In summarily, PSHP is not just a transitional technology but a long-term accelerator of a sustainable energy matrix. Thus, by addressing existing barriers and leveraging emerging opportunities, PSHP can significantly offer a platform to the global decarbonization efforts, energy security, and the achievement of net-zero emissions targets in line with sustainable development goal. Thus, leveraging on the aforementioned possibilities in PSHP, future research should focus on optimizing system efficiency, reducing costs, and exploring novel applications to ensure PSHP remains at the forefront of the renewable energy sustainability revolution.

Authors' Contributions

All aspects of the research and manuscript preparation were carried out by the author. The author has read and approved the final version of the manuscript.

Data Availability

All data are included in the text.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The author confirms consent for the publication of this work.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

References

[1] Haes Alhelou, H., Hamedani Golshan, M. E., Njenda, T. C., & Siano, P. (2019). A survey on power system blackout and cascading events: Research motivations and challenges. *Energies*, *12*(4), 682. https://doi.org/10.3390/en12040682

[2] Kia, S., Khanmohammadi, S., & Jahangiri, A. (2023). Experimental and numerical investigation on heat transfer and pressure drop of SiO2 and Al2O3 oil-based nanofluid characteristics through the different helical tubes under constant heat fluxes. *International Journal of Thermal Sciences*, *185*, 108082. https://doi.org/10.1016/j.ijthermalsci.2022.108082

[3] Salman, H. M., Pasupuleti, J., & Sabry, A. H. (2023). Review on causes of power outages and their occurrence: Mitigation strategies. *Sustainability*, *15*(20), 15001. https://doi.org/10.3390/su152015001

[4] Kia, S., Flesch, T. K., Freeman, B. S., & Aliabadi, A. A. (2021). Atmospheric transport over open-pit mines: The effects of thermal stability and mine depth. *Journal of Wind Engineering and Industrial Aerodynamics*, *214*, 104677. https://doi.org/10.1016/j.jweia.2021.104677

[5] Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. *Progress in Energy*, *3*(2), 22003. https://doi.org/10.1088/2516-1083/abeb5b

[6] Mitali, J., Dhinakaran, S., & Mohamad, A. A. (2022). Energy storage systems: A review. *Energy Storage and Saving*, *1*(3), 166–216. https://doi.org/10.1016/j.enss.2022.07.002

[7] Ramos, H. M., Sintong, J. E., & Kuriqi, A. (2024). Optimal integration of hybrid pumped storage hydropower toward energy transition. *Renewable Energy*, *221*, 119732. https://doi.org/10.1016/j.renene.2023.119732

[8] Pomianowski, M. Z., Johra, H., Marszal Pomianowska, A., & Zhang, C. (2020). Sustainable and energy-efficient domestic hot water systems: A review. *Renewable and Sustainable Energy Reviews*, *128*, 109900. https://doi.org/10.1016/j.rser.2020.109900

[9] Abdelshafy, A. M., Jurasz, J., Hassan, H., & Mohamed, A. M. (2020). Optimized energy management strategy for grid connected double storage (Pumped storage-battery) system powered by renewable energy resources. *Energy*, *192*, 116615. https://doi.org/10.1016/j.energy.2019.116615

[10] Botterud, A., Levin, T., & Koritarov, V. (2014). *Pumped storage hydropower: Benefits for grid reliability and integration of variable renewable energy*. https://publications.anl.gov/anlpubs/2014/12/106380.pdf

[11] Das, P., Das, B. K., Mustafi, N. N., & Sakir, M. T. (2021). A review on pump-hydro storage for renewable and hybrid energy systems applications. *Energy Storage*, *3*(4), e223. https://doi.org/10.1002/est2.223

[12] Charles Rajesh Kumar, J., & Majid, M. A. (2024). Advances and development of wind--solar hybrid renewable energy technologies for energy transition and sustainable future in India. *Energy & Environment*, *35*(5), 2517–2565. https://doi.org/10.1177/0958305X231152481

[13] Kishore, T. S., Patro, E. R., Harish, V., & Haghighi, A. T. (2021). A comprehensive study on the recent progress and trends in development of small hydropower projects. *Energies*, *14*(10), 2882. https://doi.org/10.3390/en14102882

[14] McIlwaine, N., Foley, A. M., Morrow, D. J., Al Kez, D., Zhang, C., Lu, X., & Best, R. J. (2021). A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems. *Energy*, *229*, 120461. https://doi.org/10.1016/j.energy.2021.120461

[15] Hunt, J. D., Zakeri, B., Lopes, R., Barbosa, P. S. F., Nascimento, A., De Castro, N. J., & Wada, Y. (2020). Existing and new arrangements of pumped-hydro storage plants. *Renewable and Sustainable Energy Reviews*, *129*, 109914. https://doi.org/10.1016/j.rser.2020.109914

[16] Airoboman, A. E., Apeh, S. T., & Sanusi, U. A. (2022). Design and simulation of an effective backup power supply for academic institutions in Nigeria: A case study of NDA postgraduate school. *Journal of Advances in Science and Engineering*, *6*, 13–19. https://doi.org/10.37121/jase.v6i1.179

[17] Gevorkov, L., & Kirpichnikova, I. (2021). Model of solar photovoltaic water pumping system for domestic application. *2021 28th International Workshop on Electric Drives: Improving Reliability of Electric Drives (IWED)* (pp. 1–5). IEEE. https://doi.org/10.1109/IWED52055.2021.9376393

[18] Pan, W., Zhu, Z., Liu, T., Liu, M., & Tian, W. (2021). Optimal control for speed governing system of on-grid adjustable-speed pumped storage unit aimed at transient performance improvement. *IEEE Access*, *9*, 40445–40457. https://doi.org/10.1109/ACCESS.2021.3063434

[19] Nduhuura, P., Garschagen, M., & Zerga, A. (2021). Impacts of electricity outages in urban households in developing countries: A case of Accra, Ghana. *Energies*, *14*(12), 3676. https://doi.org/10.3390/en14123676

[20] Uwineza, L., Kim, H. G., & Kim, C. K. (2021). Feasibility study of integrating the renewable energy system in Popova Island using the Monte Carlo model and HOMER. *Energy Strategy Reviews*, *33*, 100607. https://doi.org/10.1016/j.esr.2020.100607

[21] Julai, N., & Buswig, Y. M. Y. (2020). Hybrid renewable system based pumped energy storage for the electrification of rural areas. *In 2020 13th International Unimas Engineering Conference (ENCON)* (pp. 1–6). IEEE. https://doi.org/10.1109/EnCon51501.2020.9299334

[22] Majidi, M., Rodriguez-Garcia, L., Parvania, M., & Mosier, T. M. (2020). Integration of small pumped storage hydropower units in water distribution system operation. *In 2020 IEEE Power & Energy Society General Meeting (PESGM)* (pp. 1–5). IEEE. https://doi.org/10.1109/PESGM41954.2020.9281717

[23] Motjoadi, V., Adetunji, K. E., & Joseph, M. K. (2020). Planning of a sustainable microgrid system using homer software. *In 2020 Conference on Information Communications Technology and Society (ICTAS)* (pp. 1–5). IEEE. https://doi.org/10.1109/ICTAS47918.2020.233986

[24] Shirinda, K., Kusakana, K., & Koko, S. P. (2020). Optimal power dispatch of a grid-connected photovoltaic with groundwater pumped-hydro storage system supplying a farmhouse. in 2020 international conference on smart grid and clean energy technologies (ICSGCE). *In 2020 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)* (pp. 5–9). IEEE. https://doi.org/10.1109/ICSGCE49177.2020.9275604

[25] Uzum, B., Onen, A., Hasanien, H. M., & Muyeen, S. M. (2020). Rooftop solar pv penetration impacts on distribution network and further growth factors—a comprehensive review. *Electronics*, *10*(1), 55. https://doi.org/10.3390/electronics10010055

[26] Pickard, W. F. (2011). The history, present state, and future prospects of underground pumped hydro for massive energy storage. *Proceedings of the IEEE*, *100*(2), 473–483. https://doi.org/10.1109/JPROC.2011.2126030

[27] Guarnieri, M. (2023). The development of hydroelectricity after 1900 [Historical]. *IEEE Industrial Electronics Magazine*, *17*(4), 66–96. https://doi.org/10.1109/MIE.2023.3323909

[28] Ragheb, M. (2014). Solar thermal power and energy storage historical perspective. *Nuclear Power Engineering*, *52*. http://www.magdiragheb.com/NPRE 498ES Energy Storage Systems/Solar Thermal Power and Energy Storage Historical Perspective.pdf

[29] Sims, G. P. (1991). Hydroelectric energy. *Energy Policy*, *19*(8), 776–786. https://doi.org/10.1016/0301-4215(91)90047-R

[30] Storli, P.-T. (2022). Overview of pumped hydro resource. *Advances in Energy Storage: Latest Developments From R&D to the Market*, 211–238. https://doi.org/10.1002/9781119239390.ch12

[31] Ghoniem, A. F. (2011). Needs, resources and climate change: Clean and efficient conversion technologies. *Progress in Energy and Combustion Science*, *37*(1), 15–51. https://doi.org/10.1016/j.pecs.2010.02.006

[32] Islam, M. M., Hasanuzzaman, M., Pandey, A. K., & Rahim, N. A. (2020). Modern energy conversion technologies. In *Energy for Sustainable Development* (pp. 19–39). Elsevier. https://doi.org/10.1016/B978-0-12-814645-3.00002-X

[33] Rodrigues, E. M. G., Godina, R., Santos, S. F., Bizuayehu, A. W., Contreras, J., & Catalao, J. P. S. (2014). Energy storage systems supporting increased penetration of renewables in islanded systems. *Energy*, *75*, 265–280. https://doi.org/10.1016/j.energy.2014.07.072

[34] Khosravani, M. R., & Haghighi, A. (2022). Large-scale automated additive construction: overview, robotic solutions, sustainability, and future prospect. *Sustainability*, *14*(15), 9782. https://doi.org/10.3390/su14159782

[35] Martinot, E. (2016). Grid integration of renewable energy: Flexibility, innovation, and experience. *Annual Review of Environment and Resources*, *41*(1), 223–251. https://doi.org/10.1146/annurev-environ-110615-085725

[36] Kohlhepp, P., Harb, H., Wolisz, H., Waczowicz, S., Müller, D., & Hagenmeyer, V. (2019). Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies. *Renewable and Sustainable Energy Reviews*, *101*, 527–547. https://doi.org/10.1016/j.rser.2018.09.045

[37] Palizban, O., & Kauhaniemi, K. (2016). Energy storage systems in modern grids—Matrix of technologies and applications. *Journal of Energy Storage*, *6*, 248–259. https://doi.org/10.1016/j.est.2016.02.001

[38] Lu, B., Stocks, M., Blakers, A., & Anderson, K. (2018). Geographic information system algorithms to locate prospective sites for pumped hydro energy storage. *Applied Energy*, *222*, 300–312. https://doi.org/10.1016/j.apenergy.2018.03.177

[39] Ghorbani, N., Makian, H., & Breyer, C. (2019). A GIS-based method to identify potential sites for pumped hydro energy storage-case of Iran. *Energy*, *169*, 854–867. https://doi.org/10.1016/j.energy.2018.12.073

[40] Spyrou, I. D., & Anagnostopoulos, J. S. (2010). Design study of a stand-alone desalination system powered by renewable energy sources and a pumped storage unit. *Desalination*, *257*(1–3), 137–149. https://doi.org/10.1016/j.desal.2010.02.033

[41] Deane, J. P., Gallachóir, B. P. Ó., & McKeogh, E. J. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews*, *14*(4), 1293–1302. https://doi.org/10.1016/j.rser.2009.11.015

[42] Debevoise, T. M. (1980). The role of the federal energy regulatory commission in licensing small hydroeletric projects. *Vermont Law Review*, 279. https://access.heinonline.com/HOL/LandingPage?handle=hein.journals/vlr5&div=17&id=&page=

[43] Witt, A. M., Hadjerioua, B., Martinez, R., & Bishop, N. (2015). *Evaluation of the feasibility and viability of modular pumped storage hydro (m-PSH) in the United States*. https://www.researchgate.net/profile/Adam-Witt-2/publication/282809414

[44] Sale, M. J., Bishop Jr, N. A., Reiser, S. L., Johnson, K., Bailey, A. C., Frank, A., & Smith, B. (2014). *Opportunities for energy development in water conduits*. Oak Ridge, Tennessee: Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/files/Pub50715.pdf

[45] Canales, F. A., Beluco, A., & Mendes, C. A. B. (2015). A comparative study of a wind hydro hybrid system with water storage capacity: Conventional reservoir or pumped storage plant? *Journal of Energy Storage*, *4*, 96–105. https://doi.org/10.1016/j.est.2015.09.007

[46] Shield, S. A., Quiring, S. M., Pino, J. V, & Buckstaff, K. (2021). Major impacts of weather events on the electrical power delivery system in the United States. *Energy*, *218*, 119434. https://doi.org/10.1016/j.energy.2020.119434

[47] Campbell, R. J., & Lowry, S. (2012). *Weather-related power outages and electric system resiliency*. https://www.congress.gov/crs_external_products/R/PDF/R42696/R42696.4.pdf

[48] Panteli, M., & Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, *127*, 259–270. https://doi.org/10.1016/j.epsr.2015.06.012

[49] Gopal, C., Mohanraj, M., Chandramohan, P., & Chandrasekar, P. (2013). Renewable energy source water pumping systems—A literature review. *Renewable and Sustainable Energy Reviews*, *25*, 351–370. https://doi.org/10.1016/j.rser.2013.04.012

[50] Strang, K. D. (2017). Innovative closed-loop underground pumped hydroelectricity geothermal storage system. *International Journal of Environmental Studies*, *74*(3), 363–385. https://doi.org/10.1080/00207233.2017.1288060

[51] Habeeb, P., Gupta, L., & Prabhakar, P. (2024). Approximate conformance checking for closed-loop systems with neural network controllers. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, *43*(11), 4322–4333. https://doi.org/10.1109/TCAD.2024.3445813

[52] Saulsbury, J. W. (2020). *A comparison of the environmental effects of open-loop and closed-loop pumped storage hydropower*. https://inl.elsevierpure.com/en/publications/a-comparison-of-the-environmental-effects-of-open-loop-and-closed/

[53] Ebrahimi, S., Riasi, A., & Kandi, A. (2021). Selection optimization of variable speed pump as turbine (PAT) for energy recovery and pressure management. *Energy Conversion and Management*, *227*, 113586. https://doi.org/10.1016/j.enconman.2020.113586

[54] Ahmed, A. A., Moharam, B. A., & Rashad, E. E. (2022). Improving energy efficiency and economics of motor-pump-system using electric variable-speed drives for automatic transition of working points. *Computers and Electrical Engineering*, *97*, 107607. https://doi.org/10.1016/j.compeleceng.2021.107607

[55] Xu, Q., Zhao, H., Lyu, W., Peng, X., Yang, D., Wang, B., & Zhang, Z. (2023). Optimization of an operation strategy for variable speed pumped storage power system flexibility. *Electronics*, *13*(1), 104. https://doi.org/10.3390/electronics13010104

[56] Steenkamp, D. M. (2018). *A techno-economic study of a pump storage hydropower system for ultra-deep level mines applied to driefontein no. 9 shaft* [Thesis]. https://repository.nwu.ac.za/server/api/core/bitstreams/c6d856bb-75a7-4151-bbc5-9bea980fc710/content

[57] Nikolaos, P. C., Marios, F., & Dimitris, K. (2023). A review of pumped hydro storage systems. *Energies*, *16*(11), 4516. https://doi.org/10.3390/en16114516

[58] Liu, H., Brown, T., Andresen, G. B., Schlachtberger, D. P., & Greiner, M. (2019). The role of hydro power, storage and transmission in the decarbonization of the Chinese power system. *Applied Energy*, *239*, 1308–1321. https://doi.org/10.1016/j.apenergy.2019.02.009

[59] Carravetta, A., Derakhshan Houreh, S., & Ramos, H. M. (2018). Pumps as turbines: Fundamentals and applications. Springer. https://doi.org/10.1007/978-3-319-67507-7

[60] Reis, A. L., Lopes, M. A. R., Andrade Campos, A., & Henggeler Antunes, C. (2023). A review of operational control strategies in water supply systems for energy and cost efficiency. *Renewable and Sustainable Energy Reviews*, *175*, 113140. https://doi.org/10.1016/j.rser.2022.113140

[61] Rimpel, A., Krueger, K., Wang, Z., Li, X., Palazzolo, A., Kavosi, J., Naraghi, M., Creasy, T., Anvari, B., Severson, E., & Broerman, E. (2020). Mechanical energy storage. In T*hermal, mechanical, and hybrid chemical energy storage systems* (pp. 139–247). Academic Press. https://doi.org/10.1016/B978-0-12-819892-6.00004-6

[62] Gao, Q., Ding, B., Ertugrul, N., & Li, Y. (2022). Impacts of mechanical energy storage on power generation in wave energy converters for future integration with offshore wind turbine. *Ocean Engineering*, *261*, 112136. https://doi.org/10.1016/j.oceaneng.2022.112136

[63] Katsaprakakis, D. Al, Christakis, D. G., Stefanakis, I., Spanos, P., & Stefanakis, N. (2013). Technical details regarding the design, the construction and the operation of seawater pumped storage systems. *Energy*, *55*, 619–630. https://doi.org/10.1016/j.energy.2013.01.031

[64] Kumar, P., Singh, S., Kumar, V., & Ahuja, V. K. (2023). Hydro Power Plant. *Applied Science and Engineering Journal for Advanced Research*, *2*(3), 10–13. https://doi.org/10.54741/asejar.2.3.4

[65] Yaseen, Z. M., Ameen, A. M. S., Aldlemy, M. S., Ali, M., Abdulmohsin Afan, H., Zhu, S., & Tao, H. (2020). State-of-the art-powerhouse, dam structure, and turbine operation and vibrations. *Sustainability*, *12*(4), 1676. https://doi.org/10.3390/su12041676

[66] Gatte, M. T., & Kadhim, R. A. (2012). *Hydro power.* Energy Conservation, 9(51000), 95-124. https://doi.org/10.5772/52269

[67] Edeoja, A. (2016). Investigation of the effect of penstock configuration on the performance of a simplified pico-hydro system. *British Journal of Applied Science & Technology. 14*(5), 1-11. https://doi.org/10.9734/BJAST/2016/23996 %0A

[68] Bogenrieder, W. (2006). 6. Pumped storage power plants: 2 Hydroelectric power. In *Renewable Energy* (pp. 165-196). Berlin. https://doi.org/10.1007/10858992_7

[69] Micangeli, A., Evangelisti, S., & Sbordone, D. (2012). Alternative Energy: Hydropower. *Encyclopedia of Environmental Management, Four Volume Set, 201.* https://iris.uniroma1.it/handle/11573/413154

[70] Anagnostopoulos, J. S., & Papantonis, D. E. (2007). Pumping station design for a pumped-storage wind-hydro power plant. *Energy Conversion and Management*, *48*(11), 3009–3017. https://doi.org/10.1016/j.enconman.2007.07.015

[71] Pal, N., & Khan, F. A. (2021). Hydropower technology. In *Sustainable Fuel Technologies Handbook* (pp. 91–120). Elsevier. https://doi.org/10.1016/B978-0-12-822989-7.00005-6

[72] Hino, T., & Lejeune, A. (2012). *Pumped storage hydropower developments*. Elsevier. https://doi.org/10.1016/B978-0-08-087872-0.00616-8

[73] Islam, M. R., Aziz, M. T., Alauddin, M., Kader, Z., & Islam, M. R. (2024). Site suitability assessment for solar power plants in Bangladesh: A GIS-based analytical hierarchy process (AHP) and multi-criteria decision analysis (MCDA) approach. *Renewable Energy*, *220*, 119595. https://doi.org/10.1016/j.renene.2023.119595

[74] Ardizzon, G., Cavazzini, G., & Pavesi, G. (2014). A new generation of small hydro and pumped-hydro power plants: Advances and future challenges. *Renewable and Sustainable Energy Reviews*, *31*, 746–761. https://doi.org/10.1016/j.rser.2013.12.043

[75] Ramos, J. S., & Ramos, H. M. (2009). Sustainable application of renewable sources in water pumping systems: Optimized energy system configuration. *Energy Policy*, *37*(2), 633–643. https://doi.org/10.1016/j.enpol.2008.10.006

[76] Neto, P. B. L., Saavedra, O. R., & Ribeiro, L. A. S. (2015). Optimization of electricity generation of a tidal power plant with reservoir constraints. *Renewable Energy*, *81*, 11–20. https://doi.org/10.1016/j.renene.2015.03.011

[77] Kishor, N., Saini, R. P., & Singh, S. P. (2007). A review on hydropower plant models and control. *Renewable and Sustainable Energy Reviews*, *11*(5), 776–796. https://doi.org/10.1016/j.rser.2005.06.003

[78] Morabito, A., & Hendrick, P. (2019). Pump as turbine applied to micro energy storage and smart water grids: A case study. *Applied Energy*, *241*, 567–579. https://doi.org/10.1016/j.apenergy.2019.03.018

[79] Vasudevan, K. R., Ramachandaramurthy, V. K., Venugopal, G., Ekanayake, J. B., & Tiong, S. K. (2021). Variable speed pumped hydro storage: A review of converters, controls and energy management strategies. *Renewable and Sustainable Energy Reviews*, *135*, 110156. https://doi.org/10.1016/j.rser.2020.110156

[80] Fang, H., Chen, L., Dlakavu, N., & Shen, Z. (2008). Basic modeling and simulation tool for analysis of hydraulic transients in hydroelectric power plants. *IEEE Transactions on Energy Conversion*, *23*(3), 834–841. https://doi.org/10.1109/TEC.2008.921560

[81] Singh, V. K., & Singal, S. K. (2017). Operation of hydro power plants-a review. *Renewable and Sustainable Energy Reviews*, *69*, 610–619. https://doi.org/10.1016/j.rser.2016.11.169

[82] Bazmi, A. A., & Zahedi, G. (2011). Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review. *Renewable and Sustainable Energy Reviews*, *15*(8), 3480–3500. https://doi.org/10.1016/j.rser.2011.05.003

[83] Capilla, J. A. J., Carrión, J. A., & Alameda Hernandez, E. (2016). Optimal site selection for upper reservoirs in pump-back systems, using geographical information systems and multicriteria analysis. *Renewable Energy*, *86*, 429–440. https://doi.org/10.1016/j.renene.2015.08.035

[84] de Oliveira, G. C., Bertone, E., & Stewart, R. A. (2022). Challenges, opportunities, and strategies for undertaking integrated precinct-scale energy--water system planning. *Renewable and Sustainable Energy Reviews*, *161*, 112297. https://doi.org/10.1016/j.rser.2022.112297

[85] Elkadeem, M. R., Younes, A., Sharshir, S. W., Campana, P. E., & Wang, S. (2021). Sustainable siting and design optimization of hybrid renewable energy system: A geospatial multi-criteria analysis. *Applied Energy*, *295*, 117071. https://doi.org/10.1016/j.apenergy.2021.117071

[86] Bohra, S. S., & Anvari Moghaddam, A. (2022). A comprehensive review on applications of multicriteria decision-making methods in power and energy systems. *International Journal of Energy Research*, *46*(4), 4088–4118. https://doi.org/10.1002/er.7517

[87] Sharif, M. N., Haider, H., Farahat, A., Hewage, K., & Sadiq, R. (2019). Water--energy nexus for water distribution systems: A literature review. *Environmental Reviews*, *27*(4), 519–544. https://doi.org/10.1139/er-2018-0106

[88] Soha, T., & Hartmann, B. (2022). Complex power-to-gas plant site selection by multi-criteria decision-making and GIS. *Energy Conversion and Management: x*, *13*, 100168. https://doi.org/10.1016/j.ecmx.2021.100168

[89] Ghasempour, R., Nazari, M. A., Ebrahimi, M., Ahmadi, M. H., & Hadiyanto, H. (2019). Multi-criteria decision making (MCDM) approach for selecting solar plants site and technology: A review. *International Journal of Renewable Energy Development*, *8*(1), 15. https://www.researchgate.net/profile/H-Hadiyanto/publication/330836858

[90] Sharma, P., Verma, A., Sharma, A., Verma, P., & Bandyopadhyay, S. (2022). An integrated site selection criterion for aquifer storage and recovery. *Journal of Irrigation and Drainage Engineering*, *148*(5), 4022009. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001674

[91] Solomon, K. H., El Gindy, A. M., & Ibatullin, S. R. (2007). Planning and system selection. *Design and Operation of Farm Irrigation Systems, 2nd Edition*, 57–75. https://elibrary.asabe.org/abstract.asp?aid=23686