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Review

A Review of Pumped Hydro Storage Systems

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Abstract: With the increasing global demand for sustainable energy sources and the intermittent nature of renewable energy generation, effective energy storage systems have become essential for grid stability and reliability. This paper presents a comprehensive review of pumped hydro storage (PHS) systems, a proven and mature technology that has garnered significant interest in recent years. The study covers the fundamental principles, design considerations, and various configurations of PHS systems, including open-loop, closed-loop, and hybrid designs. Furthermore, the review highlights the crucial role of PHS systems in integrating renewable energy sources, mitigating peak load demands, and enhancing grid stability. An in-depth analysis of current and emerging trends, technical challenges, environmental impacts, and cost-effectiveness is also provided to identify potential areas for future research and development. The paper concludes by offering a perspective on the challenges and opportunities that PHS systems present, underlining their potential to significantly contribute to a sustainable and reliable energy future.

Keywords: hydro energy; pumped storage; energy storage; mechanical storage; RES; RES penetration; policy and incentives

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1. Introduction

1.1. Background and Significance of Pumped Hydro Storage Energy Systems

The global energy landscape is undergoing a significant transformation as societies transition towards more sustainable, low-carbon energy systems. This shift is driven by a growing awareness of the need to mitigate climate change, reduce dependence on fossil fuels, and ensure energy security. The increased adoption of renewable energy sources, such as solar and wind power, has been central to this transition. However, these sources are often intermittent in nature [1], leading to challenges in providing a stable and continuous supply of electricity to end users, as well as maintaining grid stability. Moreover, the interplay between water, energy, and land is becoming increasingly important in the context of sustainable development, with the UN's Sustainable Development Goals (SDGs) emphasizing the need to optimize these interactions to minimize adverse impacts on the environment while meeting societal and economic demands [2–4]. Pumped hydro storage (PHS) systems (also known as pumped storage system—PHS) have emerged as a viable response to these challenges, offering an effective solution to store energy, support renewable energy integration, and maintain grid stability while contributing to the achievement of multiple SDGs.

At its core, a pumped hydro storage system is a large-scale, reversible energy storage technology that utilizes the potential energy of water to store and release electricity. By capitalizing on the simple principle of converting electrical energy into potential energy, and vice versa, PHS systems have proven to be a vital component in modern power grids, balancing supply and demand and facilitating the integration of renewable energy sources. Figure 1 presents a typical layout of a PHS system connected to the grid.

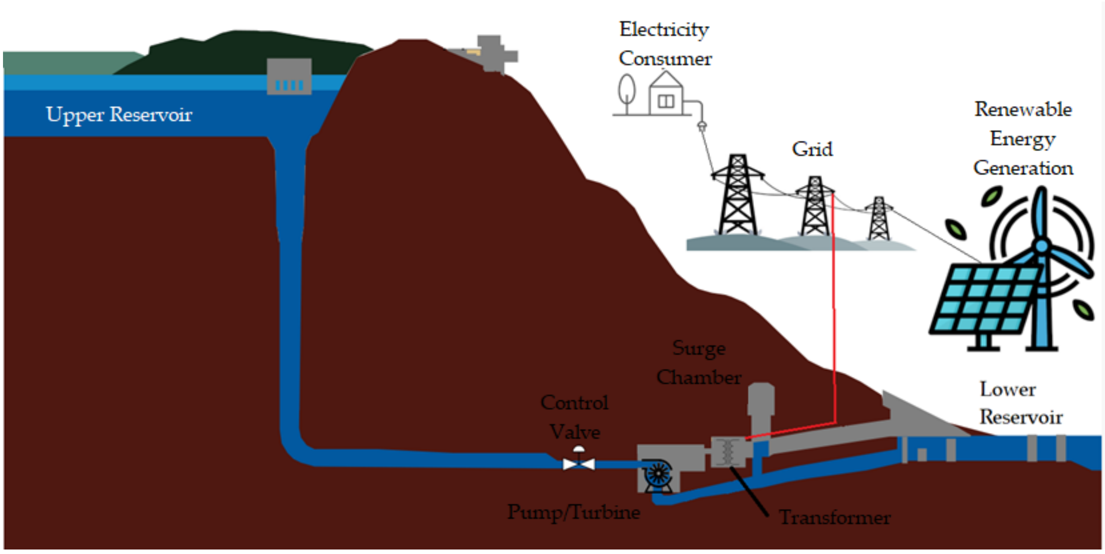

Figure 1. A possible layout of a PHS system.

In recent years, pumped hydro storage systems (PHS) have represented 3% of the total installed electricity generation capacity in the world and 99% of the electricity storage capacity [5], which makes them the most extensively used mechanical storage systems [6]. The position of pumped hydro storage systems among other energy storage solutions is clearly demonstrated by the following example. In 2019 in the USA, PHS systems contributed to 93% of the utility-scale storage power capacity and over 99% of the electrical energy storage (with an estimated energy storage capacity of 553 GWh). In contrast, by the end of 2019, all other utility-scale energy storage projects combined, such as batteries, flywheels, solar thermal with energy storage, and natural gas with compressed air energy storage, amounted to a mere 1.6 GW in power capacity and 1.75 GWh in energy storage capacity. These data underscore the significant role pumped hydro storage systems play in the United States in terms of power capacity and energy storage capacity [7].

However, these systems also come with their own set of challenges that must be taken into consideration. One significant challenge is the requirement for suitable geological formations for storage reservoirs. These reservoirs need to allow for significant water level variations to store substantial amounts of water and energy. In plain regions, storage reservoirs may impose considerable land requirements, leading to higher evaporation rates and increased capital costs for storing relatively small amounts of water and energy. Additionally, the development of PHS projects may face challenges related to environmental and social impacts, technical constraints in the design and operation of turbines and pumps, and the need for substantial upfront investments. To overcome these challenges and unlock the full potential of PHS as a viable response to renewable energy integration and grid stability, it is crucial to carefully evaluate site-specific conditions; invest in research and development to advance technological innovations; and foster partnerships among stakeholders to address environmental, social, and economic concerns.

Brief Historical Review

Pumped hydro storage is a well-established and commercially acceptable technology for utility-scale electricity storage and has been used since as early as 1890 in the region between Switzerland and Italy [8,9]. In 1929, the first North American PHS system was installed on the Housatonic River in Connecticut. The first commercial PHS system in the world was the Pedreira Elevatory Plant in Cubatão/SP, Brazil, which started operations in 1939 [9].

The early adoption of PHS plants was fueled by the favorable geographic conditions and plentiful hydro resources present in those areas. To be viable, PHS plants necessitate specific site conditions, including a high head, advantageous topography, suitable geotechnical conditions, access to electricity transmission networks, and water availability. Initial PHS plants were constructed in the Alpine regions of Switzerland and Austria, which are characterized by abundant hydro resources and appropriate topography [10].

Between the 1960s and the late 1980s, the chronological development of PHS in many countries was primarily driven by energy security concerns and nuclear energy growth following the oil crisis in the early 1970s. PHS development had remained slow until the 1960s, but the search for secure energy alternatives in the wake of the oil crisis led to a significant increase in the construction of PHS plants. This was particularly evident in countries striving to ensure energy security and support the growth of nuclear power as PHS was closely correlated with nuclear development.

PHS plants have been built in various countries, such as the USA and Japan, to complement high inertia nuclear power plants and serve as fast-response peaking plants. This strong correlation between PHS development and nuclear power plant construction in the USA and Japan demonstrates how PHS provided critical support for these facilities. Meanwhile, in Europe, countries such as Austria, which lack nuclear installations but have a rich hydro topography, have developed PHS primarily to enhance the operation and efficiency of large-scale hydropower plants [10,11].

The 1990s witnessed a decline in the development of new PHS plants, primarily due to growing environmental concerns and the scarcity of suitable sites [10]. As the most cost-effective locations became saturated and nuclear development growth waned, fewer facilities were constructed during this period. However, the landscape changed after 2000 as a renewed interest in PHS emerged, driven by the increasing demand for renewable energy sources and the liberalization of electricity markets. This shift led to the development of several large PHS plants in Europe, such as Goldisthal in Germany with a capacity of 1060 MW and Kopswerk II in Austria with a capacity of 450 MW, as countries sought to diversify their energy portfolios and integrate renewable energy sources [8,10,12].

In conclusion, this brief historical review of PHS systems showcases their importance and versatility as they have continually adapted to different drivers and technologies over the years. Initially supporting nuclear power development and addressing energy security concerns, PHS has since evolved to integrate variable renewable energy sources, highlighting its potential to remain a valuable component of the ever-changing energy landscape. The provision of ancillary services, such as balancing, frequency stability, and black starts, underscores the vital role PHS plays in modern power systems management. The long-standing adaptability and relevance of PHS serve as a testament to its significance in the ongoing pursuit of sustainable, robust, and efficient energy systems.

1.2. Scope and Objective of the Review

This review aims to provide a comprehensive analysis of pumped hydro storage (PHS) systems, addressing various aspects of their design, operation, and impacts across different scales. While the analysis covers PHS systems of all sizes, it is important to note that the quantitative analysis and statistical findings are primarily based on a dataset that includes a significant number of large systems with an installed generation power over 1000 MW. This focus on larger systems is to avoid bias and ensure a comprehensive assessment and completeness of the dataset via data cross-validation by available English references. Nevertheless, the qualitative insights and discussions encompass the broader spectrum of PHS systems, recognizing the similarities and key characteristics that extend to systems of various sizes. The scope of the review includes a range of topics to offer a holistic understanding of PHS and its potential role in the transition towards more sustainable energy systems.

In Section 2, this review will cover the characteristics and aspects of PHS, including its types, components, and uses. Section 3 will discuss the environmental impacts and sustainability considerations associated with these systems. Section 4 will present a review of policies, regulations, and international incentives relevant to the development and implementation of PHS. In Section 5, an economic analysis and feasibility assessment will be conducted to evaluate the financial viability of PHS projects. Section 6 will provide a statistical analysis of the current state of PHS deployment worldwide. Section 7 will delve into the technological advancements in the field, highlighting innovations that could enhance the performance and cost-effectiveness of PHS systems. Section 8 will identify the challenges and opportunities facing the PHS industry, offering insights into the future growth and expansion of this technology. Finally, Section 9 will conclude the review by summarizing the key findings and offering recommendations for further research and developments in the area of pumped hydro energy storage.

2. Characteristics and Aspects of Pumped Hydro Storage Systems

2.1. Characteristics and Uses of PHS

Several detailed comparative studies [6,13,14] have been performed in recent years on energy storage systems, consistently indicating that pumped hydro storage (PHS) systems have seen wide-ranging implementation due to their notable attributes such as large energy storage and power capabilities, long-term storage potential, and exceptional operational efficiency [13]. For a broader understanding of energy storage systems, readers keen on further investigation may consult these numerous comparative studies as the focus of this review primarily lies outside the extensive field of general energy storage systems.

Pumped hydro storage systems have gained prominence as viable energy storage solutions, owing to their potential to integrate renewable energy sources and provide grid stability [15–17]. Currently, PHS systems primarily serve peak generation, grid stability, and ancillary services while also facilitating the integration of variable renewables by storing excess energy generated during low-demand periods [18].

Pumped hydro storage systems (PHS) exhibit technical characteristics that make them suitable for the bulk storage of surplus variable renewable energy sources [8,11,19,20]. It is noteworthy that PHS systems have a technology readiness level of 11/11 according to the IEA guide [21]. Power capacities range from 10 to 4000 MW, providing flexibility in system design [11,14,22]. The discharge duration at rated power varies between 1 and 24+ h, accommodating storage durations from hours to days. With a round-trip efficiency of 70–85% and a generally negligible self-discharge [22], the system maintains efficient energy storage. The minimal response time of the PHS allows for prompt adaptation to fluctuating energy demands.

Hydropower is a capital-intensive technology, often requiring long lead times, and this is especially true for large capacity projects [18]. Therefore, power capital costs for PHS systems are within the range of USD 1000 to USD 4000 per kW (USD 2021) [10], while energy capital costs fall between USD 5 and USD 100 per kW. These costs position these systems as viable options for large-scale energy storage. In addition, a PHS system's lifetime of 40 to 60+ years contributes to its long-term reliability. Taken together, these technical characteristics demonstrate the suitability of pumped hydro storage systems for the bulk storage of surplus renewable energy.

The technical characteristics of PHS, listed below, contribute to a range of benefits for power grids:

- Energy storage: PHS systems provide large-scale energy storage capabilities, making them ideal for storing excess energy generated during periods of low demand and releasing it when demand peaks.
- Grid stability: By rapidly responding to fluctuations in supply and demand, PHS systems help maintain grid stability and avoid power outages or blackouts.
- Integration of renewables: The ability to store and release energy on demand makes PHS systems well-suited for accommodating the intermittency of renewable energy sources, thereby supporting their wider adoption.
- Load balancing: PHS systems aid in load balancing by shifting electricity generation from periods of low demand to periods of high demand, improving the overall efficiency of the power grid.

- Longevity and low environmental impact: PHS systems are characterized by long operational lifetimes and a relatively low environmental impact compared to other energy storage technologies, making them a sustainable option for power grids.

Table 1 associates these technical characteristics with the corresponding benefits for power grids.

Table 1. Correlation between Benefits and Technical Characteristics of Pumped Hydro Storage Systems.

Benefit	Corresponding Characteristics
Energy Storage	Discharge duration at rated power: 1–24+ h Power capacity: 10–4000 MW Energy storage capacity: MWh to 100 GWh
Grid Stability	Response time: minimal
Integration of Renewables	Round-trip efficiency: 70–85% Self-discharge: generally negligible
Load Balancing	Discharge duration at rated power: 1–24+ h Power capacity: 10–4000 MW
Longevity and Low Environmental Impact	Lifetime: 40–60+ years Round-trip efficiency: 70–85% Self-discharge: generally negligible

2.1.1. Ancillary Services of PHS

Pumped hydro energy storage (PHS) systems offer a range of unique advantages to modern power grids, particularly as renewable energy sources such as solar and wind power become more prevalent. PHS systems provide essential ancillary services, including frequency regulation, voltage support, load shifting, and system resilience, which help maintain grid stability and reliability [23].

Frequency regulation is critical for maintaining the balance between electricity supply and demand. PHS systems can respond rapidly to fluctuations in grid frequency, transitioning from idle to full output within 20 s to a few minutes. This swift response time allows PHS systems to compensate for sudden changes in energy generation or consumption, helping to stabilize the grid and prevent frequency deviations that could lead to system-wide disturbances or blackouts.

Voltage support is another key service provided by PHS systems. In the event of voltage fluctuations, PHS systems can quickly adjust their reactive power output, helping to maintain the voltage levels within the acceptable range. This capability is particularly valuable in grids with a high penetration of renewable energy sources as these resources can cause voltage fluctuations due to their variable and intermittent nature.

Load shifting is the process of transferring energy consumption from periods of high demand to periods of lower demand, allowing for the more efficient use of generation resources and reducing the need for peaking plants. PHS systems excel at load shifting by storing excess energy during off-peak periods and releasing it during peak demand. This flexibility enables grid operators to better manage energy resources, reduce costs, and minimize the need for additional peaking capacity.

System resilience refers to the ability of a power grid to recover from major disturbances, such as equipment failures or extreme weather events. PHS systems contribute to system resilience in several ways. First, they provide rotational inertia when the generator is spinning, compensating for the loss of inertia associated with conventional thermal generators upon their retirement. This rotational inertia helps maintain grid stability during transient events. Second, PHS systems possess black-start capability, enabling the restart of an electricity system after a complete supply collapse without needing external power to initiate the generators. This feature is crucial for restoring power to the grid quickly and efficiently following major disruptions.

In summary, PHS systems offer a range of unique advantages that are increasingly valuable as renewable energy sources become more widespread. By providing critical ancillary services such as frequency regulation, voltage support, load shifting, and system resilience, PHS systems contribute to the stability and reliability of modern power grids. Their rapid response times, flexibility, and ability to integrate seamlessly with renewable energy sources make them an essential component of future energy systems.

2.1.2. Integrated Pumped Storage with Renewable Energy Sources

Renewable energy sources, while environmentally friendly, often exhibit varying degrees of intermittency. This inherent characteristic poses challenges for consistent power production and grid stability, which are crucial for providing uninterrupted power supply to end users. Solar energy, for instance, is less intermittent compared to wind energy as wind velocity is subject to significant fluctuations due to meteorological factors. This variability directly impacts the generation of clean energy and consequently the stability of the power grid.

Grid stability concerns have grown increasingly important as renewable energy sources experience rapid expansion. For instance, the International Energy Agency (IEA) predicted in 2013 [24] that the European Union's share of electricity generated by renewables would increase from 6.9% in 2011 to 23.1% by 2035. However, Eurostat data show that by 2020, the share of electricity generated by renewables had already reached 39.0% [25]. Additionally, the share of renewable energy in installed electricity generation capacity has surpassed 50%, driven by the rapid growth of wind and solar power, as shown in Figure 2.

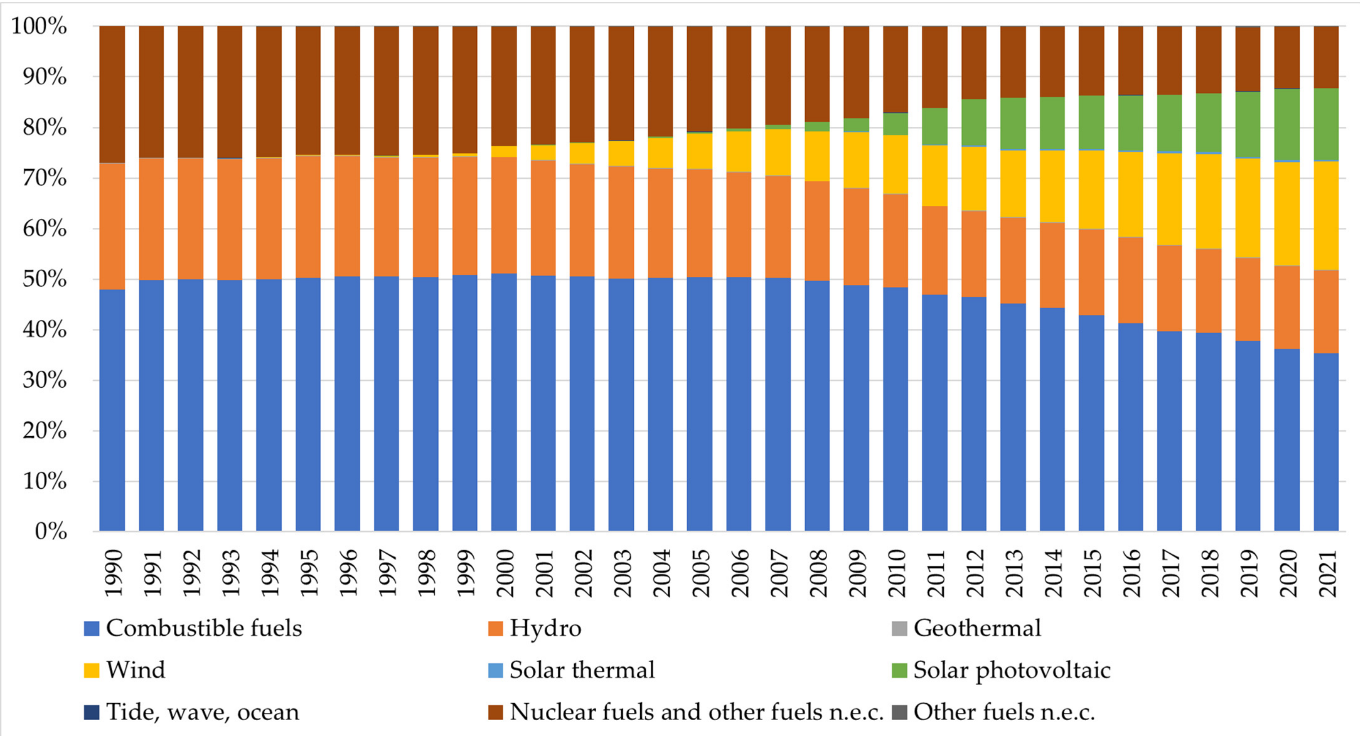

Figure 2. Share of installed electricity generation capacity (source: Eurostat database % [25]).

To tackle these challenges, bulk energy storage has been identified as an effective solution that can help reduce dependence on fossil fuels and mitigate environmental degradation [26]. By employing bulk energy storage, it is possible to manage the intermittent nature of renewable energy sources, such as wind, solar, wave, tidal, biomass, and municipal waste, and improve their capacity to deliver continuous power at their nameplate capacities [27].

Wind energy, in particular, is highly susceptible to meteorological changes, with wind speeds varying on hourly, daily, weekly, monthly, and annual scales [28]. In the particular case of isolated island grids where technical limitations are imposed and the size of the systems is limited, the energy storage option is considered to be the most effective means to increase wind penetration [29,30]. This makes it essential to incorporate energy storage systems capable of compensating for the fluctuations and ensuring reliable power generation.

Integrating pumped hydro storage systems with variable renewable energy sources, such as solar, wind, and biomass, not only enhances their ability to provide consistent power output but also contributes to the overall stability of the power grid [31]. These integrated systems combine the advantages of renewable energy generation with the storage and grid stabilization benefits of pumped storage. The stochastic nature of renewable energy sources (RES) such as solar, wind, and hydropower necessitates the importance of energy storage systems [32,33], particularly pumped hydro storage systems [14], to achieve the Paris Agreement goals of carbon neutrality in the energy sector by 2060 and limit the global temperature increase to 1.75 °C by 2100 [34].

In solar-pumped hydro storage systems, solar energy is used to power the pumps that transfer water from the lower to the upper reservoir during off-peak periods [35]. Similarly, wind–hydro systems utilize wind turbines to supply the pumping energy. Biomass-powered systems, on the other hand, use organic waste or biomass combustion to generate the required energy for pumping. These integrated systems can significantly reduce greenhouse gas emissions and fossil fuel dependency while providing a reliable and stable source of electricity.

A key challenge in integrating renewable energy sources with pumped storage systems is managing the intermittent and variable nature of renewable power generation. To address this issue, advanced control and optimization techniques, along with energy management systems, can be employed to ensure efficient operation and minimize energy losses.

2.2. Types of Pumped Hydro Storage Systems

These systems include several classification approaches based on their storage size, pump and rotation speed, storage need, configuration, and the energy sources they integrate with [36]. In this section, we will explore the classification of pumped hydro storage (PHS) systems according to their storage size, PHS arrangement, and turbine type.

2.2.1. Storage Size

Pumped hydro storage (PHS) plants can be classified based on their storage size, which directly affects their operational flexibility. A PHS system usually consists of two water reservoirs at different elevations interconnected by a system of tunnels and pipes. The various types of PHS plants are defined by the time scales on which they operate, offering different solutions for energy storage and grid support [36].

Hourly pumped hydro storage (HPHS) arrangements are primarily used for short-term adjustments to grid conditions (e.g., to provide ancillary services such as frequency balancing, harmonic removal, and backup power in case of disturbances in the supply). These plants have small reservoirs in the order of 10^6 to 10^9 m^3.

Daily pumped hydro storage (DPHS) systems are typically suitable for managing the daily fluctuations in electricity demand (day–night energy arbitrage). Although they are the most common PHS application today [8,37,38], the reduction in the cost of batteries and the decentralization of power generation might reduce the importance of this type of PHS plant in the future. Typically, these plants have reservoirs in the order of 10^6 to 10^9 m^3.

Weekly pumped hydro storage (WPHS) is designed to integrate and store energy from intermittent sources such as wind and solar [39–41]. These plants have received increased focus in recent years. These plants have small reservoirs in the order of 10^8 to $5 \cdot 10^9$ m^3.

Seasonal pumped hydro storage (SPHS) are potentially very versatile since they can be used for peak generation, ancillary services, storing intermittent wind and solar energy, hydropower optimization, and water supply [36,40,42–44]. Because SPHS plants consist of two reservoirs, a lower and an upper reservoir, they usually incur higher capital costs and therefore are not widely employed in current energy systems, but they have significant potential for the future. Typically, these plants have reservoirs in the order of 10^9 to $30{\cdot}10^9$ m^3.

Pluriannual pumped hydro storage (PAPHS) is a rare type of PHS plant that is built for storing large amounts of energy and water beyond a yearlong horizon [36]. Interest in this type of PHS plant is expected to increase due to energy and water security needs in some countries. These plants require very large reservoirs in the order of $5{\cdot}10^9$ to $100{\cdot}10^9$ m^3.

In summary, there are PHS arrangements that can cater to different purposes and operate on a wide range of time scales, offering a flexible and adaptable solution for energy storage and grid support.

2.2.2. Open-Loop and Closed-Loop Pumped and Pump-Back Storage Systems

The USA's Department Of Energy defines open-loop PHS as "continuously connected to a naturally flowing water feature" [45]. Open-loop pumped hydro energy storage (PHS) systems involve flowing a significant stream of water to either the upper or lower reservoir [46]. The major advantage of open-loop systems is their ability to utilize existing water resources and infrastructure, reducing the need for extensive land use and construction. However, these systems can cause environmental concerns due to their impact on water quality, aquatic life, and local ecosystems. Moreover, they are dependent on the availability of water resources and may be affected by seasonal variations and drought conditions. In cases in which the lower reservoir is an existing dam, the powerhouse can be built downstream of the dam, removing the need for excavation.

According to the DOE definition, closed-loop PHS is "not continuously connected to a naturally flowing water feature" [45]. So, usually, closed-loop PHS systems consist of an upper and lower reservoir far from a large water source, with limited water input; however, the term *continuously* is key in these definitions because some PHS projects are considered closed-loop even though they could withdraw water from naturally flowing surface water features initially to fill their reservoirs and periodically to replace evaporative and seepage losses [47,48]. Closed-loop systems have a reduced environmental impact compared to open-loop systems as they minimize water usage and avoid disrupting natural water bodies. Additionally, they can be located in areas where open-loop systems may not be feasible due to limited water resources. However, closed-loop systems require a substantial initial investment in reservoir construction and water supply, which may render them less cost-effective than open-loop systems. These systems can be implemented in small artificial lakes filled either by precipitation or water brought in from a different location.

Pump-back storage entails installing pump-turbines in hydropower dams with another reservoir immediately downstream, allowing water to flow back and forth between the two reservoirs. This arrangement increases flexibility and operational range as the pump-turbines can be used for both conventional hydropower generation and storage [49]. For example, during a drought, conventional hydropower generation may be reduced, but the plant can still function as a pumped storage facility. Although the head in pump-back storage plants is usually low, the system is viable since long tunnels are not required. In Japan, several dams have been built with reversible turbines.

2.2.3. Reversible Pump-Turbines and Generators

Various types of pumps and turbines are employed in pumped hydro storage systems (PHS) to facilitate efficient energy storage and conversion. The most common technologies include fixed-speed and variable-speed configurations.

Fixed-speed turbines offer constant generation and pumping capacity, which may not be ideal for complementing electricity generated from variable energy sources due to their inflexible power output. On the other hand, variable speed systems offer greater flexibility and efficiency by allowing the pump-turbine to operate at different speeds, adapting to fluctuations in power generation and consumption, especially when paired with intermittent renewable energy sources [10,12,36]. However, variable speed pump-turbines typically cost around 30–40% more than their fixed-speed counterparts and are not as widely used [50,51].

The choice between fixed and variable speed turbines depends on technical, economic, and demand factors. Although, currently, most of the larger PHS plants use fixed speed turbines [47], as the integration of intermittent renewables in the grid increases, variable speed turbines might become more popular and potentially more affordable. Variable speed pump-turbines can also operate efficiently with large head variations, which is beneficial for a wider range of operational scenarios.

Ternary systems represent another relevant technology in PHS, comprising a separate pump and turbine, along with a motor–generator set. This configuration allows for the independent operation of the pump and turbine, resulting in higher efficiency and reduced wear on the equipment. Additionally, it enables quicker switching between pumping and generating modes, further enhancing the system's responsiveness to varying power demands [52].

3. Environmental Impacts and Sustainability Considerations

3.1. Land Use and Ecosystem Alterations

The implementation of PHS systems, regardless of their power capacity size, can lead to substantial alterations in land use, particularly when constructing new reservoirs, dams, and other infrastructure. These changes can lead to habitat loss, fragmentation, and degradation, affecting local ecosystems and biodiversity. Additionally, the construction and operation of pumped hydro storage systems can alter natural water flow patterns, impacting both aquatic and terrestrial habitats.

In some cases, pumped hydro storage systems have been associated with deforestation, soil erosion, and landslides, particularly during the construction phase [53]. Appropriate planning, mitigation measures, and the selection of suitable sites can minimize these impacts. For instance, using existing reservoirs or constructing smaller closed-loop systems can help reduce land use changes and ecosystem alterations.

3.2. Water Quality and Sedimentation

The operation of pumped hydro storage systems can have significant effects on water quality, particularly in terms of temperature, oxygen levels, and nutrient concentrations. When water is stored in reservoirs, its temperature and oxygen content can change, potentially affecting downstream ecosystems. Moreover, the release of water from reservoirs can cause erosion and increased sedimentation, which may negatively impact aquatic habitats and species.

Sedimentation can lead to the loss of spawning grounds for fish and the smothering of benthic organisms, while altered water temperatures and oxygen levels can affect the survival, growth, and reproduction of aquatic species [54]. To minimize these impacts, operators can implement measures such as sediment management, selective water withdrawal, and habitat enhancement.

3.3. Greenhouse Gas Emissions

Pumped hydro storage systems are generally considered low-carbon energy storage options. However, they can still produce greenhouse gas (GHG) emissions, particularly in the form of methane (CH_4) and carbon dioxide (CO_2) from reservoirs. The decomposition of organic matter in reservoirs can result in the release of these gases, contributing to climate change.

The extent of GHG emissions from pumped hydro storage systems varies depending on factors such as reservoir size, water depth, temperature, and the amount of organic matter present. Some studies suggest that emissions can be higher in tropical regions due to warmer temperatures and higher levels of organic matter [55]. To minimize GHG emissions, strategies such as reducing reservoir surface area, promoting aerobic conditions, and avoiding deforestation can be employed.

3.4. Socioeconomic Implications

The development and operation of pumped hydro storage systems can have various socioeconomic implications, both positive and negative. On one hand, these systems can provide employment opportunities, contribute to local economic development, and enhance energy security by storing excess energy and meeting peak demand. Additionally, pumped hydro storage systems can help facilitate the integration of renewable energy sources, such as wind and solar, by storing their intermittent output and releasing it when needed [56].

On the other hand, pumped hydro storage projects can lead to the displacement of local communities, the loss of land and property, and changes in traditional livelihoods. In some cases, the construction of reservoirs and other infrastructure can require the relocation of entire communities, resulting in social and cultural disruptions. To mitigate these impacts, it is essential to involve affected communities in decision-making processes, provide fair compensation, and ensure that benefits are equitably distributed [57].

Moreover, the potential for conflicts over water resources and competing uses should be carefully considered in the planning and operation of pumped hydro storage systems. By adopting integrated water resources management approaches, promoting stakeholder engagement, and considering the needs of all users, conflicts can be minimized, and sustainable solutions can be achieved.

4. Policies, Regulations, and Incentives

4.1. International and National Policies

In composing the present subsection of the review, the selection of focus regions was driven by a carefully considered rationale that aimed to capture the most pertinent aspects of the pumped hydro storage (PHS) landscape. The decision to specifically highlight the global perspective along with the perspectives of the European Union, the United States, and Asia (with an additional focus on China) was primarily driven by their significant installed capacities and their distinctive policy and regulatory environments.

The European Union and the United States were chosen due to their comparable installed capacities of PHS systems, along with their similarly complex regulatory frameworks, which can be likened to those of other federations. These regions, with their diverse member states or territories, present unique challenges and opportunities that are worthy of separate discussion.

In the case of Asia, the vast installed capacity of PHS systems, particularly in China and Japan, exceeds other regions globally. However, it is important to note that Asia is a highly diverse region, with substantial disparities between different countries in terms of development stage, energy needs, and policies. Therefore, it was deemed essential to examine China separately, considering its global leadership in PHS system installations and its unique policy landscape.

This structure allowed us to provide a more granular understanding of the current PHS situation and its nuanced variations across these pivotal regions, all of which are shaping the global trajectory of energy storage and renewable integration.

4.1.1. Global Energy Policies and the Role of Pumped Hydro Storage

The transition to a more sustainable low-carbon energy system is a priority for countries worldwide. International organizations, such as the United Nations (UN) and the International Energy Agency (IEA), have set ambitious targets for the deployment of renewable energy and the reduction in greenhouse gas (GHG) emissions [58]. To achieve these targets, policymakers have increasingly recognized the need for flexible and reliable energy storage solutions, including pumped hydro storage systems (PHS).

PHS can help address the challenges of integrating variable renewable energy sources, such as wind and solar power, into the grid by providing grid stability, load leveling, and peak shaving services [56,59]. The IEA has identified energy storage as a critical component for the future energy system and highlights the potential of PHS in its annual World Energy Outlook reports [60].

However, the role of electricity storage, including PHS, sits in the gray area between generation and transmission [61]. Because a PHS facility's net power output is negative—recapturing only about 70 to 80% of power inputs—it is not classified as a power-generating facility [62]. Therefore, for PHS to effectively function as large-scale energy storage, it must participate in the day-ahead electricity market as a prosumer (a producer–consumer), necessitating the use of bidding and offering curves [63].

4.1.2. European Union Policies and Initiatives

In the European Union (EU), the promotion of renewable energy and energy storage has been a key policy focus. The EU's Renewable Energy Directive (2009/28/EC) set binding targets for member states to achieve a 20% share of renewable energy in their gross final energy consumption by 2020, with a subsequent update to 32% by 2030 [64]. Building on the 20% target for 2020, the recast Renewable Energy Directive 2018/2001/EU established a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023 [65,66]. Additionally, the Clean Energy Package [67] includes several measures to encourage the deployment of energy storage, such as the removal of regulatory barriers and the establishment of a clear legal framework for storage operators [66,68].

The EU has also funded several research and innovation projects related to PHS via its Horizon 2020 program. These projects [69,70] aim to improve the efficiency, flexibility, and environmental performance of PHS, as well as to explore innovative concepts, such as hybrid and offshore pumped storage systems.

4.1.3. United States Policies and Incentives

In the United States, federal and state-level policies have played an essential role in promoting renewable energy and energy storage. The USA's Department of Energy (DOE) has identified energy storage as a solution for grid stability via the Energy Storage Systems Program (DOE OE/ESSP) [12,71]. At the federal level, the Federal Energy Regulatory Commission (FERC) has issued several orders to facilitate the integration of energy storage into wholesale electricity markets, such as Order No. 841 (2018) [72], which requires grid operators to establish market rules for energy storage resources. The Department of Energy's Hydropower Vision report underpins its commitment to pumped storage systems, emphasizing clean energy innovation, grid reliability, and sustainable hydropower expansion as vital components for tackling climate change and bolstering national energy security [45]. In October 2017, FERC announced a revised policy on license terms (for both original licenses and relicenses) in which the default term became 40 years [7]. The American Water Infrastructure Act of 2018 (AWIA) directed FERC to introduce an expedited licensing process—2 years from license application to final decision—for qualifying NPDs and closed-loop PHS projects [7].

Various tax incentives and grants have also been available for the development of PHS projects such as the Investment Tax Credit (ITC) [73], which would expand tax credits for batteries that have at least 5 kilowatt hours of capacity and would expand the tax credits to residential properties that include battery storage with at least 3 kilowatt hours of capacity. At the state level, several states have adopted energy storage mandates and targets, as well as policies, to encourage the deployment of storage systems in general, such as California's Assembly Bill 2514 in 2010 [74] and New York's Energy Storage Roadmap (2018) [75].

4.1.4. Asian Policies and Strategies

Asia has experienced rapid growth in renewable energy and energy storage in recent years, driven by supportive policies and ambitious targets in countries such as China, India, and Japan.

In India, the Ministry of New and Renewable Energy (MNRE) has set ambitious targets for renewable energy capacity, aiming to reach 175 GW by 2022 and 450 GW by 2030. To support the integration of renewable energy, the Indian government has launched various initiatives related to energy storage, including the National Energy Storage Mission (2018) [76]. In 2023, the Ministry of Power issued "Guidelines on Promoting the Development of Pumped Storage Power", which aims to facilitate the deployment of PHS systems [77] by implementing policies that include setting construction deadlines with the possibility of extension, offering exemptions on land acquisition fees, providing government land at concessional rates, supporting projects via concessional climate finance, and utilizing sovereign green bonds for financing.

Due to Japan's limited fossil fuel resources, the country has historically focused on nuclear energy for base electricity generation. The intention was to utilize hydroelectric power, specifically pumped storage systems, as peak units. Japan's geography, characterized by mountainous terrain and abundant water resources, is ideally suited for the development of pumped storage systems. Consequently, a significant emphasis has already been placed on hydroelectric and pumped storage technologies, to the point that most available sites for the construction of large scale hydroelectric facilities have been used [10]. However, following the Fukushima disaster, Japan has implemented various policies to promote renewable energy and energy storage [78]. The Japanese government has set a target of 24% renewable energy by 2030 and has introduced feed-in tariffs to support the deployment of various renewable energy technologies, including PHS [79]. Furthermore, Japan's Ministry of Economy, Trade, and Industry (METI) has launched several initiatives to support the research and development of advanced energy storage technologies, including the "Innovative Technology Strategy for Energy Conservation" [80].

4.1.5. China Policies and Strategies

China has been experiencing rapid growth in electricity demand and renewable energy deployment, resulting in increased interest in pumped hydro storage systems (PHS) as a means to support grid stability and integrate renewable energy sources. The country has the largest installed capacity of PHS in the world, with over 30 GW of operational projects by the end of 2020 and ambitious plans for further expansion in the coming years [11]. Chinese policymakers have recognized the strategic importance of PHS for the country's energy transition and have been implementing a range of policies, regulations, and incentives to promote the development and deployment of these systems.

The National Development and Reform Commission (NDRC) of the People's Republic of China has gradually established and improved the mechanism of the formation of pumped storage tariffs, which played an important role in promoting the sound development of PHS systems [81]. Still, with the continued reform of the electricity market, the development of PHS has also faced problems, such as insufficient convergence with market development and inadequate incentives [82]. More recently, the Chinese government has outlined its vision for PHS development in several key policy documents, such as the "13th Five-Year Plan for Energy Development" (2016–2020) [83].

At the regional level, provincial governments have also developed specific plans and strategies for PHS deployment, taking into account local resource availability, grid conditions, and renewable energy targets. For example, provinces with abundant hydropower resources, such as Yunnan and Sichuan, have prioritized the development of large-scale PHS projects to support the integration of renewables and enhance regional grid stability [27].

4.2. Possible Policy Revisions to Facilitate PHS Growth

While significant progress has been made in promoting PHS via international and national policies, several challenges remain [84]. More specifically, the adoption of pumped hydro storage systems (PHS) faces the following policy challenges, which can vary depending on the region and local context. Some of the main challenges include the following:

- Regulatory frameworks: Outdated regulatory structures may not adequately recognize the benefits of energy storage or may even inadvertently create barriers to the development of PHS projects. Regulatory reforms are needed to ensure that PHS can participate fairly in electricity markets and be compensated for the services they provide.
- Market design and incentives: Electricity markets should be designed to properly value the flexibility and grid services that PHS can provide, such as frequency regulation, voltage support, and load shifting. Incentives, such as tax credits, subsidies, or grants, can help overcome the high upfront costs of PHS projects and facilitate investment. However, in many cases, it is reported that climate policy may not incentivize storage utilization, especially when firms that hold a dominant position in storage operation own a limited portfolio of generation assets [85].
- Environmental and social concerns: PHS projects can have significant environmental and social impacts, such as land use changes, water resource management issues, and the displacement of local communities. Policymakers need to develop frameworks that carefully consider and mitigate these impacts while still promoting the development of PHS.
- Integration with renewable energy policies: As the penetration of variable renewable energy sources such as wind and solar increases, PHS can play a crucial role in managing their intermittency. Policymakers should consider PHS as an integral part of their renewable energy strategies, ensuring that support policies and targets are aligned with the need for energy storage.
- Permitting and approval processes: Lengthy and complex permitting and approval processes can hinder the development of PHS projects. Streamlining these processes and providing clear guidelines can help to reduce project delays and uncertainties for developers.
- Research, development, and innovation: Policymakers should encourage research and development in PHS technologies to drive innovation and reduce costs. This can be achieved via funding programs; demonstration projects; and collaboration between the government, industry, and research institutions.
- International collaboration: Cross-border PHS projects can provide significant benefits in terms of resource sharing and regional grid stability. Policymakers should work with their counterparts in neighboring countries to develop collaborative frameworks and harmonize regulations to facilitate such projects.

4.3. Proposed Policies for Shaping PHS Financial Incentives and Market Factors

The successful deployment of PHS requires supportive policy measures, including incentives and financial support, market design and compensation, and integration with renewable energy policies.

Incentives and financial support are essential to encourage investment in PHS projects, which often have high upfront costs and lengthy development timelines. Governments can provide a range of financial incentives to help overcome these barriers and make PHS projects more economically viable. One potential approach is to offer grants or low-interest loans to developers, which can reduce the initial capital expenditure and lower the cost of financing. Tax credits or other fiscal incentives can also help improve a project's financial performance and attract private investment. Furthermore, feed-in tariffs or other performance-based incentives can be used to guarantee a minimum revenue stream for PHS projects, thus reducing the risks associated with market fluctuations and uncertainties.

A well-designed electricity market is crucial for ensuring that PHS projects are fairly compensated for the services they provide to the grid. Currently, many electricity markets do not adequately value the flexibility and ancillary services offered by PHS, such as frequency regulation, voltage support, load shifting, and system resilience. Policymakers can introduce new market mechanisms specifically designed to value and compensate for these services. For example, separate markets for ancillary services can be established, allowing

PHS workers to participate and be compensated for their contributions. Additionally, existing market rules can be revised to better accommodate and value the services provided by PHS, such as updating bidding rules, timeframes, or compensation structures to ensure fair market participation.

Capacity markets, where available, can also play an essential role in supporting PHS projects. By ensuring that PHS is eligible to participate and be compensated for its contribution to resource adequacy, capacity markets can create an additional revenue stream and enhance the financial viability of these projects. Moreover, energy arbitrage—the ability to store energy during periods of low demand and release it during periods of high demand—is another valuable service provided by PHS. Policymakers should ensure that market designs facilitate and reward this service, thus creating additional revenue opportunities for pumped storage projects.

Finally, pumped hydro storage systems (PHS) should be incorporated into long-term energy planning, and their contribution to system reliability and flexibility should be evaluated. Encouraging innovation and cost reduction in both RES and PHS technologies, while fostering collaboration between stakeholders (e.g., via knowledge-sharing platforms, joint research initiatives, and public-private partnerships) is essential.

5. Economic Analysis and Feasibility

5.1. Capital Costs and Investment Requirements

Pumped hydro storage (PHS) systems entail substantial initial capital costs, making the evaluation of capital expenses and investment requirements crucial to determining the feasibility and financial viability of such projects. The term Total Capital Cost has been used used by Zakeri [12]. Capital costs for PHS facilities are influenced not only by the installed power but also by the energy storage and MW capacity at a specific site, demonstrating their highly site-specific nature [12].

According to Deane [10], capital costs, which typically range from 1000 to 4000 USD/kW, encompass the expenses associated with the construction and installation of pumps, turbines, generators, transformers, and other equipment necessary for energy conversion and transmission, as well as civil engineering work for the energy storage. A study conducted by the EPRI in 1988 [86] estimated the costs to range between USD 500 and USD 1000 excluding transmission costs (the USD values are adjusted to reflect 2021 levels based on inflation rates from the FRED2 database [87]).

The rise in costs for PHS projects has been attributed to factors such as higher licensing expenses, increased costs for implementing more efficient and reliable plants, and construction delays due to technical and financial challenges [10]. Furthermore, the most suitable sites, which were less expensive to construct and offered high capacity, have already been utilized. Investment requirements for PHS projects can be substantial, as they often involve large-scale infrastructure development, land acquisition, and the procurement of specialized equipment. An important observation is that the construction and installation costs of pumped hydro storage (PHS) systems are estimated to be approximately twice as high as those of conventional hydropower plants with similar capacity [88]. However, the long operational lifetimes of these systems (40–60+ years), their benefits towards grid stability, and their capacity for bulk energy storage can help offset the initial capital costs over time. This provides a return on investment and contributes to the overall cost-effectiveness of PHS facilities.

One significant challenge that PHS systems face in terms of capital investment is the potential for escalating initial cost estimations due to unforeseen delays and unexpected site-specific factors, which can also lead to long lead times for these projects. For example, despite accounting for project contingencies, the capital costs of a 1000 MW upgrade PHS project were initially announced at EUR 810 M in 2009 [10], but later revised to 1700 MEUR in 2014. The typical project contingency for PHS systems is estimated to be between 10–15%, while the accuracy of cost estimations varies from −20 to +25% [5].

The primary cause for cost variations is the uncertainty in storage costs, particularly for storage reservoirs, as the Power Conversion Systems (PCS) section is comprised of mature technologies. Storage reservoir costs can vary significantly, ranging from usd 10/kWh to USD 169/kWh [50]. Factors influencing these costs include site-specific features and plant size; for instance, a 14.4 GWh plant has a storage cost of USD 69/kWh (52 EUR /kWh), whereas an 11.7 GWh storage capacity incurs a cost of USD 103/kWh (77 EUR /kWh) [50]. Zakeri et al. [12] estimated that the average capital costs for power conversion systems and storage are EUR 513/kW and EUR 68/kWh, respectively.

To attract investment and secure funding for PHS projects, it is essential to demonstrate the long-term financial viability and potential environmental benefits of these systems. Because the costs are so site specific, this can only be achieved through comprehensive feasibility studies, cost–benefit analyses, and assessments of the project's alignment with regional and national energy policies.

5.2. Operation and Maintenance Costs

Operation and maintenance (O&M) costs play a vital role in the long-term viability and performance of pumped hydro storage (PHS) systems. These costs encompass the expenses associated with the ongoing upkeep, repair, and management of PHS facilities, ensuring their safe, efficient, and reliable operation throughout their extended lifetimes. O&M costs include routine inspections, periodic maintenance of equipment such as pumps, turbines, and generators, as well as any necessary repairs or replacements due to wear and tear.

It is important to note that the cost of charging energy is not part of the O&M costs. The cost of charging energy is not part of the O&M costs in the context of LCOE because it refers to the price of electricity needed to pump water to the upper reservoir in a Pumped Hydro storage system, rather than the expenses related to operation and maintenance. This cost is influenced by factors such as electricity price volatility, liberalized energy markets, and varying sources of charging energy, such as nuclear or wind power. In a liberalized market, fluctuating energy prices and the generation mix cause charging energy costs to vary, depending on factors such as time of day, season, or availability of low-cost electricity. Separating charging energy costs from O&M costs allows for a more accurate representation of distinct cost components involved in the operation of Pumped Hydro storage systems and their impact on LCOE calculations.

It is important to note that each PHS installation is unique, with different requirements and characteristics, which may affect O&M costs accordingly. While the initial capital costs of PHS projects can be substantial, O&M costs are generally more manageable in comparison. The relatively low maintenance requirements of PHS systems, coupled with their long operational lifetimes (40–60+ years), contribute to their overall cost-effectiveness and appeal as a large-scale energy storage solution. However, it is crucial to allocate sufficient resources for O&M activities to prevent equipment failure, ensure system reliability, and maximize the return on investment.

To optimize O&M costs and maintain the long-term performance of PHS facilities, it is essential to implement a comprehensive and proactive maintenance strategy tailored to the specific needs of each installation. This involves conducting regular inspections, adhering to equipment manufacturers' recommended maintenance schedules, and utilizing advanced monitoring and diagnostic tools to identify and address potential issues before they escalate. In addition, investing in staff training and skill development can help ensure that personnel are equipped to manage the complex and specialized systems that comprise PHS facilities effectively.

The Energy Storage Grand Challenge Cost and Performance Assessment 2020 [89] estimated and presented the operation and maintenance (O&M) costs for two different PHS system sizes: 100 MW and 1000 MW (see Table 2, in which both are outlined with a 10 h power generation duration. For the 100 MW system, labor-related fixed O&M costs amount to USD 15.7/kW-year, parts-related fixed O&M costs are USD 5.6/kW-year, and refurbishment-related fixed O&M costs stand at USD 9.0/kW-year. The total fixed O&M cost for the 100 MW system is USD 30.4/kW-year, which represents 2.0% of the capital cost. On the other hand, the 1000 MW system has a significantly lower labor-related fixed O&M cost at USD 3.1/kW-year. However, the parts-related and refurbishment-related fixed O&M costs remain the same at USD 5.6/kW-year and USD 9.0/kW-year, respectively. The total fixed O&M cost for the 1000 MW system is USD 17.8/kW-year, accounting for 1.4% of the capital cost. The table highlights the economies of scale in labor-related O&M costs when comparing the two system sizes.

Table 2. PHS O&M costs per category (based on [89]).

Component	100 MW System	1000 MW System
Duration (hrs)	10	10
Labor-related fixed O&M (USD/kW-year)	15.7	3.1
Parts-related fixed O&M (USD/kW-year)	5.6	5.6
Refurbishment-related fixed O&M (USD/kW-year)	9.0	9.0
Total fixed O&M (USD/kW-year)	30.4	17.8
Percentage of capital cost (%)	2.0	1.4

5.3. Levelized Cost of Electricity (LCOE)

The levelized cost of electricity (LCOE) is a key metric used to evaluate the long-term economic viability of energy generation projects, including pumped hydro storage (PHS) systems. LCOE represents the average cost per unit of electricity generated over the lifetime of an energy project, taking into account initial capital costs, operation and maintenance costs, fuel costs, and other relevant factors. By comparing the LCOE of different energy generation technologies, policymakers and investors can make informed decisions regarding the most cost-effective and sustainable options for power generation.

It is essential to acknowledge that each PHS installation has unique characteristics and requirements, which can affect the LCOE accordingly. Factors such as site-specific construction and engineering costs, reservoir size, local energy market conditions, and the operating philosophy of the plant can all influence the LCOE of a PHS project. The operating philosophy, which may include covering peak demand, ensuring grid stability and facilitating the integration of renewable energy sources, plays a crucial role in determining the LCOE. As a result, the LCOE may vary significantly across different installations, making it vital to conduct a thorough analysis of each project's specific circumstances to determine its economic viability.

Zakeri et al. [12] presented a comprehensive methodology for estimating the levelized cost of energy (LCOE) and the levelized cost of storage (LCOS) for electrical energy systems in general, which are important metrics for evaluating the economic feasibility of energy storage systems. However, these concepts fall outside the scope of this review, so a detailed discussion will not be provided here. For those interested, please refer to the original paper by Zakeri. They have identified the effect and the importance of the number of discharge cycles of electrical storage systems in general and of PHS systems in particular.

Despite the potential variability in the LCOE, PHS systems often exhibit competitive costs when compared to other large-scale energy storage and peak-power generation technologies. The long operational lifetimes (40–60+ years) and relatively low operation and maintenance costs of PHS systems contribute to their overall cost-effectiveness. Additionally, the ability of PHS to support the integration of renewable energy sources and provide grid stability services can further enhance their value proposition as these benefits align with the global transition towards more sustainable and low-carbon energy systems.

A study conducted by Lazard Financial Advisory in 2016 reported that the average unsubsidized levelized costs of storage for compressed air, pumped hydro, and lithium ion batteries are USD 128/MWh, USD 175/MWh, and USD 414/MWh [90]. In comparison the average value of LCOE for hydro power after 2013 drops below USD 100/MWh for installations greater than 10 MW [91], while an IRENA report from 2012 reported that the LCOE typically ranges from USD 20/MWh to USD 190/MWh for large installations [92,93].

5.4. Return on Investment and Payback Periods

For PHS projects, the ROI and payback periods depend on various factors, such as the initial capital costs, operation and maintenance costs, energy prices, and the revenue generated from the services provided by the system, including energy storage, grid stability, and support for renewable energy integration. The long operational lifetimes (40–60+ years) and relatively low operation and maintenance costs of PHS systems can contribute to their overall cost-effectiveness and, consequently, enhance their ROI and shorten payback periods.

However, each PHS installation is unique, and the specific circumstances of the project can significantly impact its ROI and payback period. Thus, conducting a thorough financial analysis, considering all relevant factors, is essential to determine the economic viability of an PHS project and ensure that it delivers the desired returns on investment and an acceptable payback period.

6. Statistical Analysis of Pumped Hydro Power Systems

6.1. Time Evolution of Installed Power

6.1.1. Global Trends and Patterns

Figure 3 illustrates the global trends in annual installations of pumped hydro storage (PHS) systems from 1962 to 2030. It provides insights into the operational status of PHS systems (in operation or under construction) and the cumulative power capacity in MW up to a given year. Notable periods of growth can be observed around and after the 1970s, 2000s, and 2020s.

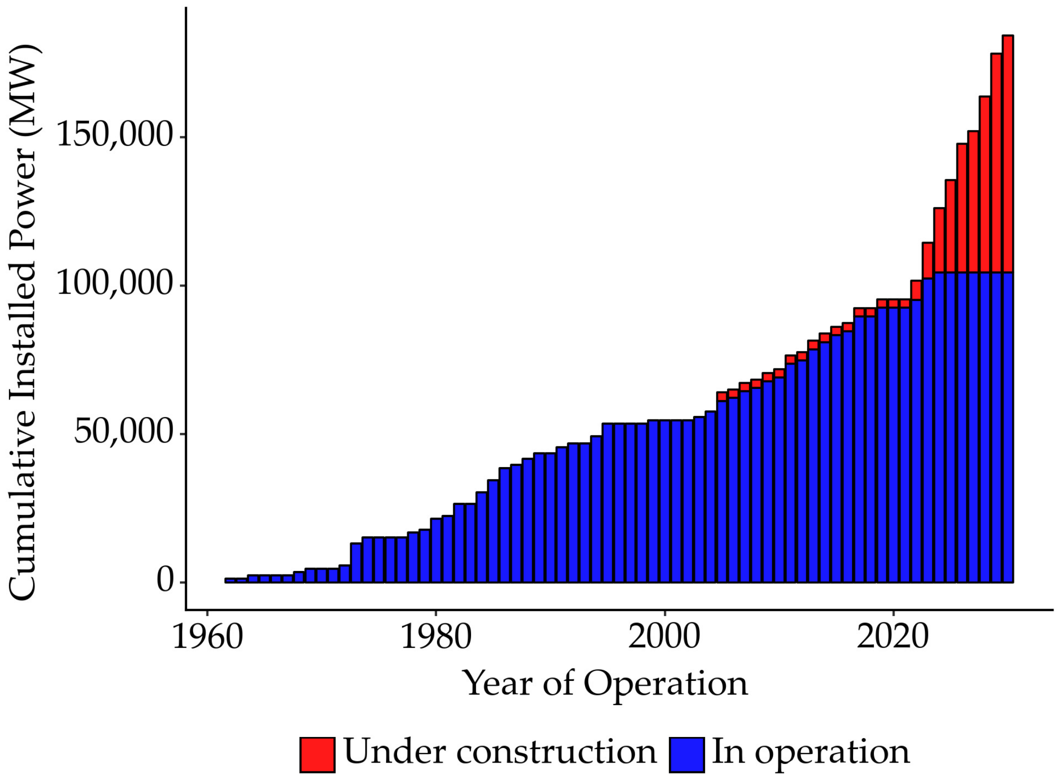

Figure 3. Cumulative installed power (MW) over time and by status, for large PHS systems that either operation or under construction.

The growth in the 1970s can be attributed to a combination of factors, including increased environmental awareness, the oil crisis of 1973, and advancements in hydroelectric technology. These factors led to a greater interest in hydroelectric power as a sustainable alternative to fossil fuels.

The surge in growth after the plateau in 2000 can be linked to rising concerns about climate change and the need to reduce greenhouse gas emissions. International agreements such as the Kyoto Protocol and the Paris Agreement have played a significant role in encouraging nations to pursue low-carbon energy alternatives, including hydroelectric power. Additionally, rapid economic growth in emerging economies such as China, India, and Brazil has increased energy demands, with hydroelectric power playing a significant role in meeting these needs. The growth during this period was further supported by technological advancements and increased investment in renewable energy infrastructure.

The anticipated growth in pumped hydro storage (PHS) systems after 2022, as depicted in Figure 3, is predominantly driven by Chinese projects. This expansion can be attributed to China's strategic energy mix planning, which emphasizes increasing the share of wind and solar energy in the country's power generation [94]. As these renewable energy sources are intermittent in nature, there is a growing need for energy storage solutions such as PHS to ensure grid stability and provide a continuous supply of electricity. Consequently, the surge in wind and solar power adoption in China has contributed to the rapid expansion of PHS systems during this period.

In the dataset, the cumulative power capacity of PHS systems exhibits a consistent upward trend, indicating the increasing importance of these storage solutions in managing grid stability and reliability amid the expansion of renewable energy generation.

Finally, the figure reveals an interesting aspect of large projects such as the Kannagawa Hydropower Plant: the considerable time required for their maturation and completion. This 2820 MW project's construction began in 2005 and will extend to 2032. However, the planning started over 10 years prior. More specifically, the Kannagawa Hydropower Field Survey Office was initiated in July 1993, and the power plant received approval from the Electric Power Development Coordination Council in July 1995. Construction began in May 1997, with the area behind the Ueno Dam inundated by October 2003 and the Minamiaiki Dam's reservoir starting to fill the following year. Both dams were completed, and the upper reservoir was filled by 2004. The first generator was commissioned on December 2005, and the second was commissioned on June 2012. The remaining units (3–6) are scheduled to be commissioned by 2032, emphasizing the extensive duration required to complete projects of this scale. The bottom line is that over half of the project's power capacity is not available.

Furthermore, as these projects span a considerable amount of time, significant technological upgrades may be implemented within the systems. For example, Unit 2 of the Kannagawa Hydropower Plant employed a "splitter runner", which allows for the simultaneous operation of both the pump and turbine blade. As a result, the generating efficiency has improved by 4%, increasing the output by 20 MW per unit.

6.1.2. Aggregated Sums per Continent

Table 3 presents the global distribution of pumped hydro storage systems, both under construction (spanning 2022–2030) and in operation. It reveals a total installed capacity of 190,822.9 MW. Asia leads the world in installed capacity, accounting for 138,057 MW, of which 77,154 MW is under construction and 60,903 MW is already operational. Europe follows with a total capacity of 27,787.9 MW, including 2480 MW under construction and 25,307.9 MW in operation. North America has a total capacity of 14,631 MW, with 900 MW under construction and 13,731 MW operational.

Africa, Australia, and South America have relatively smaller shares in the global capacity. Africa has a total capacity of 5547 MW, with 2750 MW under construction and 2797 MW in operation. Australia has 4050 MW of total capacity, 2250 MW of which is under construction and 1800 MW is operational.

Table 3. Distribution of installed and under construction power plants by continent.

Continent	In Operation	Under Construction	Total
Asia	77,154	60,903	138,057
Europe	2480	25,308	27,788
North America	900	13,731	14,631
Africa	2750	2797	5547
Australia	2250	1800	4050
Total	85,534	105,289	190,823

This distribution highlights Asia's dominance in the global pumped hydro storage market, with a substantial portion of capacity under construction, indicating a strong growth trend for the region. Europe and North America also contribute significantly to the global capacity, while Africa, Australia, and South America have comparatively smaller shares.

6.2. Aggregated Sums per Country

6.2.1. Regional and Country-Level Perspectives

Table 4 presents the operational and under construction power capacity of PHS by country. The capacity distribution is concentrated within a few key countries, with the total installed capacity reaching about 190 GW. China is the dominant player in the market, with an impressive installed capacity of 110,198 MW, which constitutes 57.8% of the global total. China has 69,550 MW of systems under construction and 40,648 MW already in operation. Japan follows with a capacity of 18,127 MW, representing 9.5% of the global total, including 2820 MW under construction and 15,307 MW operational. The United States holds the third largest share with 13,731 MW of operational systems, accounting for 7.2% of the global total, but has no capacity currently under construction.

Table 4. Installed power capacity of large PHS (over 1000 MW) systems by country.

Country	In Operation	Under Construction	Total	Refs in Operation	Refs under Construction
China	40,648	69,550	110,198	[95–121]	[102,111,122–159] [141,146,160–191]
Japan	15,307	2820	18,127	[192–205]	[206]
USA	13,731	0	13,731	[207–216]	
Italy	4200	0	4200	[217–220]	
Australia	1800	2250	4050	[221]	[222]
Ukraine	2531	900	3431	[223,224]	
Taiwan	2608	0	2608	[225,226]	
United Kingdom	2500	0	2500	[227]	
Egypt	0	2400	2400		[228]
South Africa	2332	0	2332	[229,230]	
India	0	2200	2200	[231]	[232,233]
Germany	2105	0	2105	[234,235]	
Switzerland	1000	900	1900	[236]	
France	1800	0	1800	[237,238]	
Spain	1770	0	1770	[239–241]	
Serbia	1300	0	1300		[242]
Luxembourg	1300	0	1300	[243]	
Russia	1216	0	1216	[244]	
Vietnam	0	1200	1200	[245]	
Czech Republic	1175	0	1175		
Belgium	1164	0	1164	[246]	
Iran	1040	0	1040	[247]	
Indonesia	0	1040	1040		[248]
South Korea	1000	0	1000	[249]	

Together, China, Japan, and the United States account for approximately 74.5% of the total global PHS capacity. Other countries with significant shares include Italy (4200 MW), Australia (4050 MW), and Ukraine (3431 MW). The remainder of the countries, which individually account for less than 2% of the global capacity, collectively hold approximately 25.5% of the total installed PHS capacity. Some notable countries in this group are the United Kingdom (2500 MW), Germany (2105 MW), Switzerland (1900 MW), France (1800 MW), and Spain (1770 MW).

Examining the distribution at the continental level, Asia is the leader with a total capacity of 138,057 MW, driven primarily by China and Japan. Europe follows with 27,787.9 MW of capacity, while North America has a capacity of 14,631 MW, mainly from the United States. It is worth noting that Africa, Australia, and South America have relatively smaller shares in the global capacity, with Africa at 5547 MW, Australia at 4050 MW, and South America at 750 MW.

In summary, the global PHS capacity is heavily concentrated in a few key countries, predominantly China, Japan, and the United States, which together account for nearly three-quarters of the total installed capacity. The remaining countries, while individually having smaller shares, still contribute to the global capacity. Asia leads the continents in PHS capacity, with Europe and North America following. The distribution of PHS capacity highlights the importance of these key countries and regions in shaping the future of the pumped hydro storage market.

6.2.2. Top Countries by Installed Power

To evaluate the historical and projected growth of PHS, we focused exclusively on large-scale renewable energy installations, specifically those with a capacity greater than 1000 MW. This approach allows for a better understanding of the impact of major projects and the role of leading players in the global transition to sustainable energy sources.

Figure 4 presents the total installed power per year for countries accounting for 80% of the total installed power from 1962 to 2030. By concentrating on the major contributors, we can gain a clearer understanding of the most significant drivers of renewable energy expansion. The data highlights the increasing adoption of renewable energy sources over the years, with particular emphasis on the rapid growth observed in recent decades. The United States, China, and India are among the major contributors to the global expansion of pumped hydro storage (PHS) systems. Notably, China's renewable energy capacity has experienced exponential growth from 2005 onwards, surpassing other leading nations by a significant margin. Australia and Italy have also exhibited a consistent increase in their renewable energy capacity. In contrast, Japan and India had a slower growth trajectory in earlier years, with more substantial capacity expansion observed after 2010.

China's significant increase in renewable energy capacity after 2022 cements its position as a global leader in PHS and sustainable renewable energy adoption. The recent growth observed in the data, particularly after 2022, can be attributed to the increasing adoption of stochastic and intermittent renewable energy sources, such as wind and, to a lesser degree, solar power. The rising prevalence of these fluctuating energy sources drives the demand for advanced energy storage solutions, such as PHS, to ensure grid stability and reliability, enabling the further growth of renewable energy capacity. From 2022 to the end of the data series in 2030, China's under-construction projects account for a proportion on the order of 85% of the total installed capacity by all countries combined (approximately 68 GW out of 80 GW large PHS projects that are under construction, planned, or announced). This highlights China's crucial role in shaping the global renewable energy landscape.

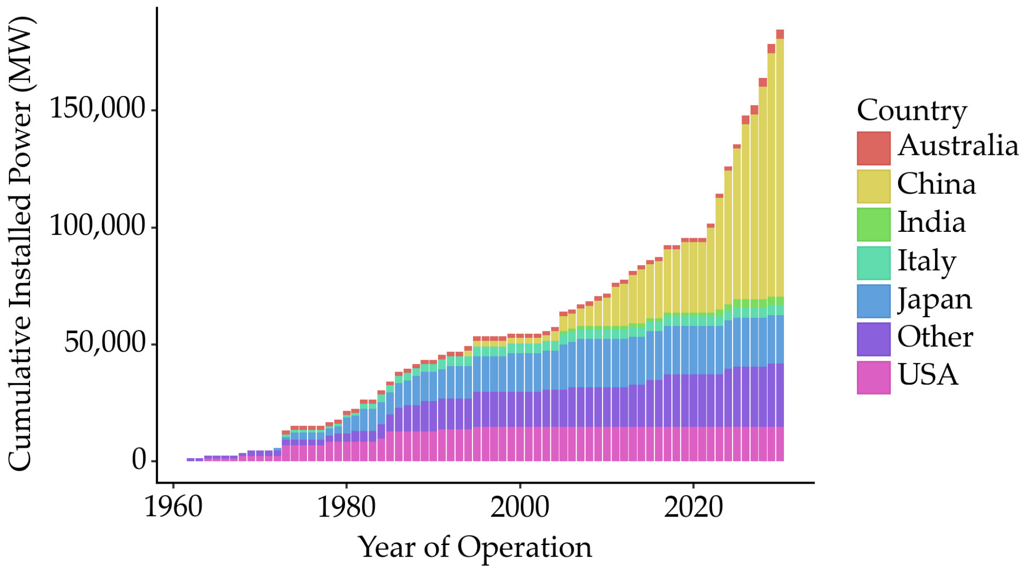

Figure 4. Total installed power capacity since 1960 by country (considering only plants that are greater than 1 GW), focusing on the countries that account for 80% of the total installed power capacity.

6.3. Historical Cost Trends

Figure 5 presents the evolution of the adjusted cost per watt for pumped hydro storage systems over the years, with a focus on the period between 1980 and 2020. The costs displayed have been adjusted according to the USA's Consumer Price Index (CPI) to reflect USD in 2021, ensuring a fair comparison across time. It should be noted that not all plants in the dataset had reliable cost data associated with them, and some even lacked any cost information at all. Despite this limitation, the graph still offers valuable insights into the changing cost structure of these energy storage systems.

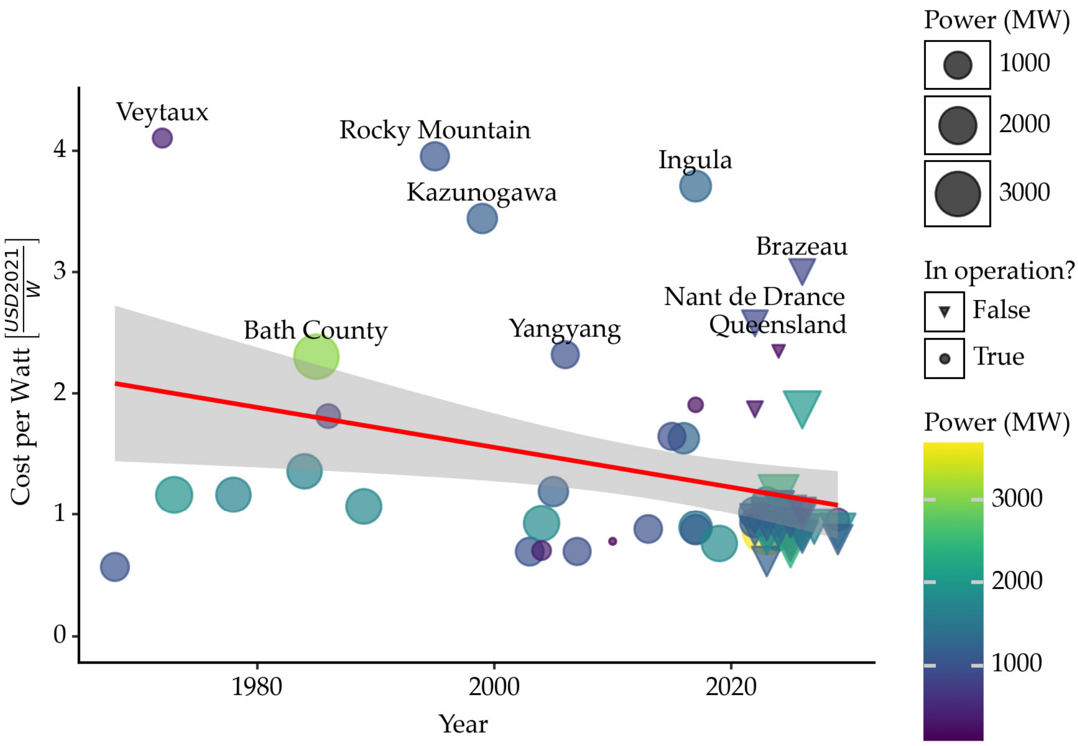

Figure 5. Evolution of Adjusted Cost per Watt for Pumped Hydro Storage Systems (USD 2021).

A key feature of the graph is the use of color and size to represent the installed power (in MW) of each pumped hydro storage system. This enables a clearer understanding of the relationship between the installed power and the cost per watt. The graph also includes a linear regression line, showing a small but steady decrease in the cost per watt over the years. The cost per watt averaged at around USD 1.7 (2021) in 1980 and gradually decreased to approximately USD 1.5 (2021) in 2020.

The graph suggests a modest decrease in the cost per watt of pumped hydro storage systems over the years. However, it is important to consider that the involved technologies are relatively mature, with limited room for significant cost reduction over time. The observed decrease in costs might be influenced by the most recent projects, which have announced budgets instead of final costs. These initial budgets are subject to change as projects progress, and the final costs could vary from the initial estimates. As a result, the downward trend in cost per watt may not be solely attributed to technological advancements or economies of scale but could also be influenced by the evolving nature of project budgets. This highlights the importance of the careful interpretation of cost trends, especially when considering mature technologies and the potential influence of budget estimations on the observed data.

More specifically, the capital costs per watt for various plants are in agreement with the literature (i.e., a range of USD 1 to 4 per watt) [10,12,250]; however, it is interesting to note that many under-construction plants appear to be clustered under the lower bound of USD 1 per watt. This phenomenon may be attributed to the underestimation of costs that often occurs at the inception of a project. Even with contingencies in place, project costs can sometimes double, leading to significant deviations from initial estimates. Consequently, the bundle of under-construction projects currently showing low values for capital costs per watt should be viewed with caution, as these figures are likely to change as the projects progress and encounter unforeseen challenges.

6.3.1. Effect of Power and Year of Commission to the Cost per Watt

In order to gain insights into the maturity of the technology and the potential influence of economies of scale, a statistical test was conducted. The test examined the relationship between the year of operation and power capacity (size of the plant) on the capital cost per watt in the dataset. An ordinary least squares (OLS) regression analysis was employed. OLS regression is a commonly used method to estimate the relationships between multiple independent variables by fitting a linear model to the data.

The results of the statistical analysis revealed the following findings. Firstly, the R-squared value of 0.132 indicated that approximately 13.2% of the variation in the cost per watt could be explained by the year of operation and power capacity. This suggests that these factors have a moderate influence on the capital cost.

Regarding the specific variables, the coefficient for the year of operation was estimated to be -0.0166 with a p-value of 0.013. This indicates a statistically significant negative relationship between the year of operation and the capital cost per watt. In other words, as the year of operation increases, the cost per watt tends to decrease. This finding suggests that the technology might become more mature over time, leading to cost reductions. Additionally, the statistical coefficient for the size of the plant (power in MW) was estimated to be -0.0003, although it was not statistically significant, with a p-value of 0.134. This implies that the size of the plant, represented by power capacity, may not have a significant effect on the capital cost per watt in the dataset. However, it is important to consider that this result might be subject to further investigation and analysis.

6.3.2. Effect of Operational Status on Cost per Watt

In order to determine whether there is a significant difference in the cost per watt between completed (operational) projects and projects that are still in the planning or under-construction phase, this analysis aimed to investigate whether the cost per watt is greater for completed projects compared to projects in the development phase. An increased cost per watt in the constructed project could be associated with unforeseen budget revisions, which are commonly observed in the construction of power plants.

To assess this, a *t*-test was performed to compare the means of the cost per watt for the two groups: operational systems and systems not yet built. The *t*-test is a statistical method used to determine if there is a significant difference between the means of two independent groups.

The results of the *t*-test indicated a t-statistic of 1.6815 and a *p*-value of 0.0991. The fact that the *p*-value is greater than the conventional significance level of 0.05 suggests that there is not a significant difference in the cost per watt between operational systems and systems not yet built. Therefore, based on this analysis, it can be concluded that the operational status (operational or under construction) does not have a significant impact on the cost per watt.

It is important to note that while the difference was not found to be statistically significant, there may still be practical or contextual considerations that could affect cost revisions. Further investigation and analysis may be required to explore potential factors that contribute to cost variations in different project stages.

6.4. Turbine Types and Characteristics

The selection of turbines and pumps for pumped hydro storage systems (PHS), particularly large-scale systems over 1000 MW, is influenced by various factors. Francis turbines are by far the most common choice due to their wide range of operational conditions and high efficiency. Kaplan and Pelton turbines are also options, but their use in PHS is less frequent. In terms of pump configuration, fixed-speed systems are predominant, offering cost-effective and proven solutions. However, only a few PHS systems incorporate variable-speed pumps, which provide better flexibility and adaptability to fluctuations in power demand. Ternary systems, with even fewer installations, combine separate pumps and turbines for independent operation, delivering higher efficiency and faster mode-switching capabilities. Overall, the choice of turbines and pumps in PHS depends on factors such as efficiency, flexibility, and compatibility with the specific project requirements and site conditions.

6.5. Head Difference and Reservoir Volume Analysis

Figure 6 illustrates the relationship between energy storage capacity, plotted on the *x*-axis using a logarithmic scale, and installed power, represented on the *y*-axis. Color coding is used to differentiate between various developmental eras of hydraulic energy storage systems, namely, early adoption, rapid expansion, stabilization, and renewed growth. Additionally, the size of the markers corresponds to the hydraulic head associated with each project.

A notable observation from the figure is the occurrence of the largest storage capacity project during the rapid expansion era (green color). This suggests that, during this period, significant drivers (e.g., nuclear energy and the goal of energy security after the oil crisis of the 1970s) led to the development of more ambitious and larger-scale projects.

In the renewed growth era, a cluster of projects is characterized by medium energy storage capacities (up to 30 GWh) and installed power close to 2000 MW. This implies that the most favorable and easily developed sites were likely utilized during the earlier periods of growth. As a result, the renewed growth era seems to be marked by a focus on optimizing and improving existing technologies and resources rather than embarking on large-scale storage projects. It is also worth considering that evolving environmental policies may have played a role in shaping this trend.

It is important to note that data for all plants were not available, limiting the comprehensiveness of the analysis. As such, the graph should be interpreted with caution and not treated as conclusive. Nonetheless, the trends depicted offer valuable insights into the historical and ongoing development of hydraulic energy storage systems across different eras.

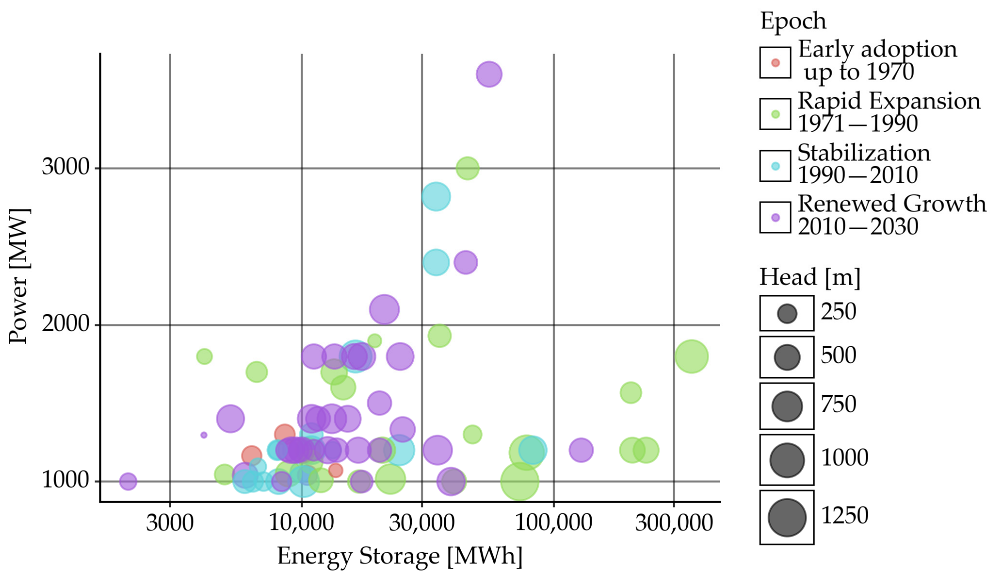

Figure 6. Evolution of PHS: Installed Power vs. Storage Capacity.

Figure 7 presented in this article features a facet grid graph that effectively demonstrates the relationship between the eras of hydraulic energy storage system development, hydraulic head, and plant size. The graph is divided into columns representing different eras, with time plotted on the *x*-axis and hydraulic head (in meters) on the *y*-axis. Each row in the facet grid corresponds to a specific size category for the plants: small (under 1000 MW), large (1000 to 2000 MW), and very large (over 2000 MW). The energy storage capacity of each project is represented by both the color and size of the markers.

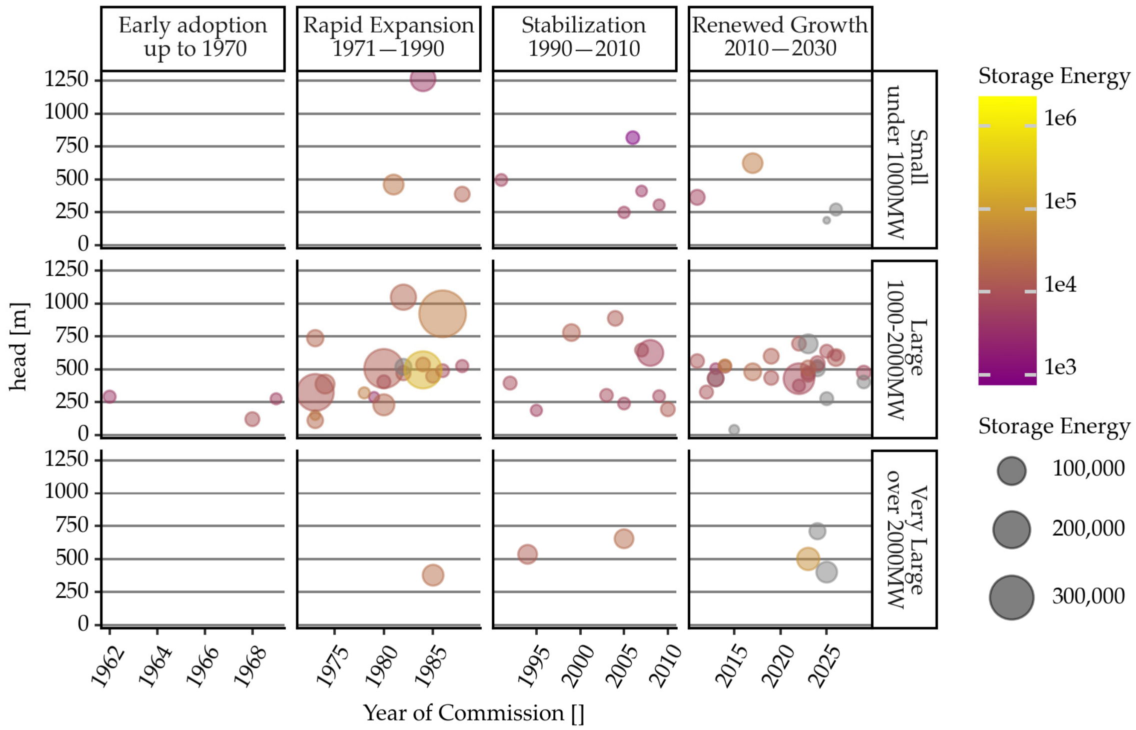

Figure 7. Comparing Hydraulic Head and Plant Size in the Developmental Eras of PHS.

Upon analyzing the graph, several trends emerge. During the early adoption phase, only a handful of medium-sized projects with relatively low hydraulic heads and energy storage capacities were undertaken. As the field progressed into the rapid expansion era, a significant increase in the number of large projects with high hydraulic heads was observed, indicating the development of more advanced and ambitious hydraulic energy storage systems.

The subsequent stabilization period saw a shift towards smaller storage projects, possibly due to the depletion of suitable sites for larger-scale developments. In the renewed growth era, although a resurgence of large projects is evident, these projects do not exhibit energy storage capacities that are as substantial as those observed during the rapid expansion phase. This could be attributed to the fact that the most favorable sites for hydraulic energy storage had already been exploited in earlier eras.

Again, it is important to bear in mind that data for all plants were not available (about 95 out of the 200 in our database), which may affect the comprehensiveness of the graph's insights. Therefore, while the identified trends offer valuable information on the historical development and current state of hydraulic energy storage systems, the graph should not be treated as entirely conclusive.

7. Technological Advancements and Innovations

Underground PHS (UPHS) and seawater PHS (SPHS) are innovative technologies that share similar working principles with conventional PHS systems, with the main difference being the type of lower reservoir utilized. In UPHS, abandoned quarries or mines serve as lower reservoirs [183], while in SPHS, the sea functions as the lower reservoir, saving construction cost and time [13]. Currently, the world's sole seawater-pumped storage hydro system, located on the northern coast of Okinawa Island, Japan, has been in operation since 1999, with the capacity to generate up to 30 MW of power [251]. In a study by Pickard [252], the feasibility of underground PHS is examined from technical, economic, and environmental aspects, indicating that excavation costs comprise 82% of the TCC for such systems. Based on [62], 25% of the permitted PHS projects in the USA by 2010 were those with at least one underground reservoir [12].

Other less common configurations of PHS include making PHS reservoirs from wastewater treatment storage bodies [62]; using a piston-floated gravity-based mechanism in an underground water-filled shaft [253]; undersea PHS connected to offshore wind plants [254]; and the storage of water and energy inside wind turbine towers [36]. Run-of-the-river SPHS plants can store water from a main river without the need for damming, thus reducing social and environmental impacts.

Another recent development in the field of energy storage is the creation of tidal and offshore pumped storage systems. These systems leverage the power of ocean tides or waves to pump water into elevated reservoirs or submerged storage facilities. During periods of high electricity demand, the stored water is released, driving turbines and generating electricity [255]. Tidal and offshore systems have the advantage of utilizing the predictable and consistent energy provided by ocean tides and waves, resulting in a highly reliable energy storage solution. Furthermore, they can be integrated with other renewable energy sources, such as offshore wind or solar installations, to enhance their overall efficiency. However, these systems face significant technical challenges, such as corrosion, high maintenance costs, and potential environmental impacts on marine life and ecosystems [256].

PHS facilities sit at a unique crossroads between power generation and transmission, a position that poses the intriguing challenge of managing a net negative power output. As we shift towards a future in which large-scale energy storage is paramount, the role of PHS facilities as 'prosumers'—both producers and consumers—becomes increasingly significant. This introduces the need for innovative strategies and technological advancements to construct effective bid and offer curves, enabling PHS to participate successfully in the day-ahead electricity market. Encouragingly, the existing literature [38,59,63] has begun to explore predictive approaches for balancing PHS supply and demand, which points towards a promising trajectory for further innovation in this sector.

8. Challenges and Opportunities

8.1. Environmental Challenges

Perhaps the most significant environmental challenge confronting PHS systems is the finite availability of suitable locations for their development. As the demand for these systems increases, it becomes evident that many of the most advantageous sites have already been utilized, while others, although potentially suitable, are designated as conservation areas or otherwise protected. Consequently, PHS systems can be viewed as finite resources, with their availability closely tied to the availability of suitable sites.

This presents a formidable challenge in the field of PHS development as it imposes constraints on where these systems can be established. It is a delicate balance between harnessing the potential of these systems to promote the utilization of renewable energy sources (RES) and maintaining the integrity of the environment we are striving to protect. It is indeed a paradoxical situation: on one hand, the development of PHS can contribute significantly to sustainable energy production; on the other hand, such developments must not compromise the health and well-being of our planet's ecosystems.

For example, PHS systems' environmental disruption may involve habitat disruption, water resource management, and potential effects on local ecosystems. The construction of PHS infrastructure may lead to land-use changes, deforestation, and soil erosion, which can alter the habitats of plants and animals. Additionally, the diversion and management of water resources may affect water quality, aquatic life, and downstream ecosystems. Addressing these issues requires comprehensive environmental assessments to be carried out before project development. In order to mitigate the impact, a multifaceted approach should be employed that incorporates innovative technological solutions (e.g., advanced pump designs or sustainable construction practices, such as erosion control and habitat restoration), regulatory frameworks, and strategic planning. Additionally, the operation process should involve identifying measures to avoid or minimize negative consequences and monitoring the implementation of these measures.

Regulatory frameworks also play a pivotal role in finding a balance between development and environmental preservation. Governments and regulatory bodies could develop and enforce guidelines that ensure the sustainable development of PHS systems. These guidelines could include mandatory environmental impact assessments, stringent site selection criteria, and regulations that encourage the use of already disturbed or industrialized land for new developments.

Strategic planning and cooperation between energy providers, government bodies, environmental organizations, and local communities can also be instrumental in addressing this challenge. By working together, these stakeholders can identify the best sites for future developments that meet the necessary requirements for PHS systems while minimizing environmental impact.

A pressing concern in the context of global hydrological cycles is the declining storage capacity of lakes worldwide [257]. Lakes, which hold a significant 87% of Earth's liquid surface fresh water, are under substantial threat from the cumulative effects of climate change and human activities. An analysis of the world's 1972 largest lakes, leveraging three decades of satellite data, climatic records, and hydrological models, revealed statistically significant decreases in storage for 53% of these bodies of water from 1992 to 2020. This finding underscores the increasing scarcity of water resources available for pumped hydro storage (PHS) systems. On a brighter note, PHS systems can double as water storage facilities, and the adoption of systems utilizing seawater has become increasingly prevalent. Nonetheless, the ongoing global reduction in lake water storage poses a formidable obstacle to the further expansion and utility of PHS systems.

Given these circumstances, it is our view that the most promising path forward lies in advancing technologies related to seawater pumped hydro systems and closed-loop underground systems. These alternatives could effectively circumvent the issues of site and freshwater availability, potentially leading to substantial advancements in the field of PHS systems.

8.2. Social Challenges

Social challenges related to PHS systems may include land acquisition, the displacement of communities, and the need for the public acceptance of the technology [258]. Land acquisition for PHS projects can result in the displacement of local communities, loss of agricultural land, and disruption of cultural and religious sites. To address these concerns, developers should engage in transparent communication and meaningful consultation with affected communities, ensuring that their needs and concerns are considered throughout the project planning and implementation process. Compensation, resettlement, and support for alternative livelihoods can help alleviate the negative impacts of land acquisition and displacement. Furthermore, fostering public acceptance of PHS technology requires education and awareness campaigns to highlight the benefits of renewable energy integration, grid stability, and the potential for long-term economic growth. By addressing social challenges in a proactive and inclusive manner, PHS projects can achieve greater acceptance and support from local communities while contributing to a more sustainable energy future.

8.3. Opportunities for Future Growth and Expansion

The future growth and expansion of PHS systems are influenced by several factors that present significant opportunities for the development and implementation of these technologies. One of the primary drivers is the increasing growth of wind and solar installations worldwide. As more countries invest in renewable energy sources to reduce their greenhouse gas emissions and combat climate change, the need for effective and efficient energy storage solutions becomes paramount. PHS systems, with their proven ability to store and release energy on demand, are well suited to accommodate the intermittency of these renewable energy sources, thereby supporting their wider adoption.

Another factor that encourages the growth and expansion of PHS is the global commitment to climate change mitigation, as reflected in the Paris Agreement. Countries around the world have pledged to reduce their carbon emissions and transition to renewable energy sources in an effort to limit global warming to well below 2 degrees Celsius above pre-industrial levels. PHS systems are in a unique position to play a crucial role in this transition by enabling the grid integration of renewable energy sources, facilitating load balancing and improving overall grid stability. Their environmental benefits, including long operational lifetimes and a relatively low environmental impact compared to other energy storage technologies, make them an attractive and sustainable option for power grids.

The maturity of PHS technology also presents an opportunity for future growth and expansion. Decades of research, development, and practical implementation have resulted in highly efficient and reliable systems that can be tailored to suit specific geographical and operational conditions. Advances in pump and turbine technology, such as the development of variable-speed and ternary configurations, have further enhanced the flexibility and efficiency of PHS systems. These technological advancements, combined with growing expertise in the design, construction, and operation of PHS facilities, contribute to the increasing attractiveness of these systems for large-scale energy storage applications.

Lastly, the technical characteristics of PHS systems, such as their wide range of power capacities (10–4000 MW), discharge durations at rated power (1–24+ h), and round-trip efficiencies (70–85%), make them highly versatile and suitable for a variety of applications. Their minimal response times and generally negligible self-discharge rates further underscore their suitability for grid-scale energy storage and the integration of intermittent renewable energy sources.

In conclusion, the opportunities for the future growth and expansion of pumped hydro storage systems are abundant, driven by factors such as the increasing adoption of wind and solar installations, global climate change commitments, the maturity of PHS technology, and their favorable technical characteristics. By harnessing these opportunities and addressing the associated environmental and social challenges, PHS systems can play a vital role in supporting the global transition towards a more sustainable and reliable energy future.

9. Conclusions

Pumped hydro storage systems offer significant benefits in terms of energy storage and management, particularly for integrating renewable energy sources into the grid. However, these systems also have various environmental and socioeconomic implications that must be carefully considered and addressed. By adopting appropriate planning, mitigation measures, and stakeholder engagement, the negative impacts of pumped hydro storage systems can be minimized, and their sustainability can be enhanced. As the global transition towards renewable energy continues, it is essential to strike a balance between the benefits of pumped hydro storage systems and their potential environmental and social costs.

This review offers an in-depth exploration of pumped hydro storage (PHS) systems, with a focus on large-scale systems featuring over 1000 MW of installed generation power. The objective is to present a holistic understanding of PHS, including their design, operation, impacts, and potential role in the transition towards sustainable energy systems. The review is organized into multiple sections, each addressing different aspects of PHS.

In Section 2, the review delves into the diverse applications of pumped hydro storage (PHS) systems, with a particular focus on their increasing adoption in conjunction with renewable energy sources. The section commences by providing a comprehensive description of the characteristics and uses of PHS, highlighting their notable benefits such as providing ancillary services to the grid and facilitating the mutually beneficial integration of renewable energy sources. Building upon this foundation, the review explores various classification systems for PHS based on the best practices identified in the existing literature. Notably, a classification scheme based on energy storage size and intended uses of PHS is emphasized as it has been found to offer valuable insights into the operational aspects of these systems. Additionally, the section covers the different configurations and types of pumps and turbines employed in PHS, thereby facilitating a thorough understanding of the various system types available in the literature.

Section 3 provides a concise qualitative overview of the environmental impacts associated with pumped hydro storage (PHS) systems, considering the significance of environmental concerns as potential project inhibitors. Given the limited scope of this article, it aims to provide readers with an overall understanding of the environmental implications rather than delving deeply into each aspect. The analysis covers land use and ecosystem alterations, water quality and sedimentation, greenhouse gas emissions and climate change, and socioeconomic implications. Each of these aspects has the potential for extensive exploration, but this review offers a comprehensive view within the constraints of its size and scope.

Section 4 provides a comprehensive analysis of incentives and initiatives for pumped hydro storage (PHS) systems globally. By adopting an unconventional classification method based on entities of similar size, the review examines the progress of PHS systems in Asia, with a particular focus on China; Europe; and the USA. The findings underscore the crucial role of government attention at the policy and legislative levels in fostering the growth of large-scale PHS projects. Notably, recent measures in China have demonstrated the positive impact of government interventions on the expansion and success of PHS systems. The section emphasizes the need for policy revisions, financial incentives, and market mechanisms to facilitate the continued development of PHS systems. It highlights the importance of proactive government involvement and supportive policies in ensuring the sustained expansion of PHS projects worldwide. These insights highlight the significance of government actions in promoting the growth and viability of large-scale PHS systems, as exemplified by recent developments aimed primarily at integration with RES in China and other regions.

Section 5 of this study delves into the economic aspects of pumped hydro storage (PHS) systems, focusing on capital costs, operation and maintenance costs, the levelized cost of electricity (LCOE), and a comparison with other energy storage technologies. By adjusting all costs for inflation, a fair comparison across different time periods is achieved. The inclusion of this section aims to provide valuable references and data regarding the cost per watt, capital costs, operation and maintenance costs, and LCOE. The analysis reveals that the capital costs of PHS systems typically range from USD 500 to 1000 (2021) per watt, excluding transmission costs. Furthermore, the LCOE for PHS is estimated to be around USD 100/MWh, highlighting its cost competitiveness compared to other energy storage technologies such as lithium batteries, which have an LCOE of USD 414/MWh. This demonstrates the potential economic advantages of PHS in the context of energy storage.

Section 6 of this study provides a comprehensive statistical analysis of the current state of pumped hydro storage (PHS) deployment worldwide. By examining the evolution of installed power, aggregated sums per country and year, and cost trends, this section offers valuable insights into the historical development and present status of PHS systems. The analysis reveals four distinct periods of development for PHS: the early adoption phase, a rapid expansion from 1970 to 1990, a stabilization period from 1990 to 2010, and a renewed growth phase over the last decade. The examination of the history of aggregated installed capacities highlights China as the current top player in PHS deployment, followed by the United States, Japan, and Europe. Furthermore, an analysis of the cost per watt indicates that PHS technologies and procedures have matured over the past 60 years, with limited room for further improvement in cost reduction. Attempts were made to determine the susceptibility of these projects to budget revisions by comparing the cost per watt for operational and under-construction projects, but the analysis yielded inconclusive results. Additionally, it is observed that the best sites for large-scale PHS projects have already been developed, and current plans focus more on smaller projects with a greater emphasis on energy storage capacity. These findings contribute to our understanding of the current landscape and trends in PHS deployment worldwide.

Sections 7 and 8 of this study delve into alternative configurations of pumped hydro storage (PHS) systems and explore the challenges and opportunities facing the industry. Building upon the findings from previous sections, these discussions offer the authors' recommended approaches and technologies that can enhance the performance and cost-effectiveness of PHS systems. Emphasis is placed on the integration of PHS with renewable energy sources, highlighting the role of PHS as prosumers and the importance of stochastic prediction for bid and offer curves. Furthermore, considering the decreasing availability of fresh water, the potential of seawater-based PHS projects as viable replacements is discussed. These sections contribute to the identification of strategies and solutions that can overcome obstacles and drive the growth and expansion of PHS systems in the future.

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Abbreviations (Alphabetically)

DPHS	Daily Hydro Energy Storage System
EU	European Union
GHE	Geothermal Heat Exchangers
GHG	Greenhouse Gas
PHS	Hydro Energy Storage System

HPHS	Hourly Pumped Hydro Storage
IEA	International Energy Agency
KPIs	Key Performance Indicators
LCOE	Levelized Cost of Energy
LCOE	Levelized Cost of Storage
PCS	Power Conversion System
PAPHS	Pluriannual Hydro Energy Storage System
RES	Renewable Energy System
SDG	Sustainable Development Goal
SPHS	Seasonal Pumped Hydro Storage
UPHS	Underground Pumped Hydro Storage
UN	United Nations
VRES	Variable Renewable Energy System
WPHS	Weekly Pumped Hydro Storage

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