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SWOT-AHP Analysis of the Importance and Adoption of Pumped-Storage Hydropower

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Abstract

Energy storage technologies are becoming increasingly important when it comes to maintaining the balance between electricity generation and consumption, especially with the increasing share of variable renewable energy sources (VRES). Pumped storage hydropower plants (PSHs) are currently the largest form of energy storage at the grid level. The aim of this study is to investigate the importance and prospects of using PSHs as part of the energy transition to decarbonize energy sources. A comparison was made between PSHs and battery energy storage systems (BESSs) in terms of technical, economic, and ecological aspects. To identify the key factors influencing the wider adoption of PSHs, a combined approach using SWOT analysis (which assesses strengths, weaknesses, opportunities, and threats) and the Analytical Hierarchy Process (AHP) as a decision support tool was applied. Regulatory and market uncertainties (13.54%) and financial inequality (12.77%) rank first and belong to the "Threats" group, with energy storage capacity (10.11%) as the most important factor from the "Strengths" group and increased demand for energy storage (9.01%) as the most important factor from the "Opportunities" group. Forecasts up to 2050 show that the capacity of PSHs must be doubled to enable the integration of 80% of VRES into the grids. The study concludes that PSHs play a key role in the energy transition, especially for long-term energy storage and grid stabilization, while BESSs offer complementary benefits for short-term storage and fast frequency regulation. Recommendations to policymakers include the development of clear, accelerated project approval procedures, financial incentives, and support for hybrid PSH systems to accelerate the energy transition and meet decarbonization targets.

Keywords: pumped storage hydropower; SWOT; AHP; renewable energy sources; grid-scale integration

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Academic Editors: Edimar José De Oliveira and Janaína Gonçalves De Oliveira

Received: 24 June 2025
Revised: 9 July 2025
Accepted: 13 July 2025
Published: 16 July 2025

Citation: Bošnjaković, M.; Veljić, N.; Božič, J.T.; Muhič, S. SWOT-AHP Analysis of the Importance and Adoption of Pumped-Storage Hydropower. *Technologies* **2025**, *13*, 305. https://doi.org/10.3390/technologies13070305

1. Introduction

Major global climate changes have steered the global energy transition towards renewable energy sources. In this context, wind farms and photovoltaic systems make the largest contribution to electricity generation. As these energy sources have an unstable, intermittent character, there is a need for energy storage at the grid level. At times when electricity generation from renewable energy sources is reduced or fails to materialize, energy from energy storage systems is used.

It can therefore be said that renewable energy technologies create instability in the electricity system, in contrast to continuous energy generation technologies (nuclear, hydroelectric, and geothermal), which ensure grid stability [1]. It is also clear that energy consumption fluctuates greatly over the course of days and months and that the electricity grid must establish a balance between energy production and consumption [2], which poses a challenge for grid management [3]. Energy storage systems are therefore crucial for maintaining the balance between generation and consumption, especially if the share of renewable energy sources (RES) continues to increase [4].

Energy from solar and wind power plants fluctuates with weather conditions on time scales ranging from less than a second to weeks or longer [2,5]. In terms of the need for variable electricity generation to balance production and demand, nuclear power plants are less flexible than fossil fuel power plants [6], whose share people are trying to decrease significantly. This means that flexibility must be ensured in other ways. Therefore, low-carbon electricity without storage poses a particular challenge for utilities [2]. Energy storage is one of the three main methods to replace flexibility in the electricity grid caused by fossil fuels [7,8]. Other methods include demand-side management, where consumers adjust their electricity consumption in terms of time or quantity, and improved grid connection, which helps to balance fluctuations in renewable energy generation and demand [5,9].

Energy storage systems help to integrate renewable energy by storing surplus wind and solar power in times of oversupply and low electricity prices [10]. In general, storage systems can take advantage of fluctuations in wholesale electricity prices by charging when prices are low and discharging when prices are high [11].

Energy storage systems can potentially improve the stability and reliability of the electricity grid. They can help to stabilize frequency and voltage, reduce power outages, and increase the resilience of the grid [12,13]. On the grid side, storage technologies provide additional services, such as continuous frequency regulation and response to unexpected changes in supply or demand [14,15].

Peak load control is an important aspect of electricity grid management. It enables more efficient use of energy resources, cost reductions, and improved grid stability. Stored energy plays a central role here, as it provides the necessary flexibility and rapid response to balance electricity demand and supply [16]. Various energy storage technologies are used for peak load management in the electricity grid, and their effective implementation brings significant economic and technical benefits to both consumers and grid operators.

The analysis of the available data from the literature clearly shows that two technologies dominate the electricity storage sector in terms of installed capacity worldwide. These two technologies are the PSH and electrochemical systems (batteries).

Pumped storage power plants are currently the largest form of energy storage at the grid level. According to data from 2023, the installed capacity of these plants worldwide is 182 GW, which corresponds to more than 90% of the total energy stored worldwide [17].

While electrochemical systems such as lithium-ion batteries are experiencing rapid growth (150 GW/363 GWh by 2024), their role remains complementary to PSHs due to limitations in long-term storage (>10 h) and cycle durability (<5000 cycles).

The historical importance of the PSH stems from its ability to provide real-time frequency regulation [18], black-start capabilities [19], and multi-hour energy storage at a levelized cost of service (LCOS) of ~60 USD/MWh—65% lower than battery systems. A black start is a very important function of PSHs, a function that battery systems do not have due to their relatively low grid capacity. A black start is the process of restoring the operation of a power plant, part of a power grid, or an industrial facility without relying on the external power transmission grid to recover from a full or partial shutdown (blackout).

Black-start systems are critical to the reliability and resilience of the power grid as they ensure a fast and efficient restoration of power after a blackout.

Other important advantages of PSHs are the long service life, the high round-trip efficiency of around 85%, and the global warming potential (GWP), which is 2–5 times lower for closed PSH systems than for lithium-ion batteries [20,21].

The energy storage landscape faces crucial challenges: the growing share of wind and solar energy and the changes in electricity demand are important factors for the increasing seasonality in all regions. In Europe, the increasing seasonality is mainly due to a six-fold increase in wind energy from 2022 to 2050 and its strong seasonality—with more production in winter—combined with an increase in temperature-dependent electricity demand, including space heating [22]. For example, energy demand in Europe increases by ~25% in winter compared to summer, but solar power generation decreases by ~60% [23]. Batteries (4–8 h) and short-term storage cannot compensate for week-long deficits. Seasonal storage bridges these gaps by storing excess solar/wind power in the summer for the winter. With the increasing share of VRES combined with new sources of electricity demand with changing demand patterns, from electric vehicles to heat pumps in homes, electricity systems will look and function differently than before, and the security of electricity supply will become increasingly important, and with it energy storage.

According to the International Hydropower Association (IHA), global PSH capacity will grow by 6.5 GW to 179 GW by 2023 [24]. Forecasts by the International Renewable Energy Agency (IRENA) show that a global net-zero scenario will require more than 325 GW of PSH capacity by 2050 [25].

Despite their advantages, the implementation of pumped storage power plants is associated with a number of challenges. High initial capital costs and geographical constraints are the main obstacles. Suitable sites with the required elevation and water resources are not always readily available. Environmental concerns, such as the potential impact on local ecosystems and landscapes, must also be considered through careful planning and regulation.

Although PSHs and battery energy storage systems (BESSs) have been extensively compared in previous research, there are still three important gaps. First, there is a gap in the integrated analysis, as most studies evaluate the technical or economic parameters separately, neglecting the synergies between the grid stabilization strengths of PSHs and the rapid response capabilities of BESSs. Second, there is a gap in strategic prioritization, as existing frameworks lack quantitative methods to assess the drivers of PSH implementation, such as environmental impacts versus revenue streams. Third, there is a gap in temporal scalability: projections beyond 2030 often underestimate the role of PSHs in 80% renewable energy scenarios, especially in relation to hybridization with green hydrogen.

These limitations hinder policymakers and investors from holistically assessing the PSH's value in decarbonization strategies.

This study addresses these gaps through a three-part methodology. First, an economic benchmarking is conducted by comparing energy costs (LCOE) and CO_2 emissions (as shown in Section 3.3) between PSHs and BESSs. Secondly, a SWOT-AHP synthesis is applied to quantify 20 strategic factors through pairwise comparisons using the Saaty scale. Finally, this study includes decarbonization modeling that projects the role of PSHs in achieving a high share of renewable energy by 2030 and 2050.

The following sections describe in detail the SWOT-AHP weighting methodology applied and present policy recommendations to accelerate the implementation of the PSH in line with the goals of increasing global renewable energy capacity and decarbonizing society by 2050.

2. Materials and Methods

The research methodology initially involved a review of the literature to obtain information on the use of the hybrid SWOT-AHP method in strategy formulation and selection. This was followed by a systematic literature search in the Web of Science and Scopus databases using the Boolean operators ("pumped-storage hydropower" OR "PSH") AND ("energy storage" OR "grid stability") AND ("SWOT-AHP" OR "multi-criteria analysis"). The inclusion criteria prioritized peer-reviewed articles (2015–2024). Additional information was extracted from technical reports and studies from the International Renewable Energy Agency (IRENA), the National Renewable Energy Laboratory (NREL), the International Energy Agency (IEA), and similar sources. Studies without quantitative LCOS comparisons or environmental impact assessments were excluded based on the exclusion criteria. Key parameters were standardized:

- Technical: Round-trip efficiency (%), hydraulic head (m), response time (s).
- Economic: LCOS (USD/MWh), CAPEX (USD/kW), payback period (years).
- Environmental: CO_2 equivalent (kg/MWh), land use (km^2/GWh).

In order to achieve the objectives of this study, the data was systematically organized according to the categories of the SWOT analysis. The SWOT method is used to identify and evaluate both internal factors—i.e., strengths and weaknesses—and external factors, such as opportunities and threats, that influence PSH technology.

A modified Delphi method was used in this study to ensure the greatest possible objectivity of the study. The modified Delphi method is a group consensus strategy in which the literature review, stakeholder opinion of stakeholders, and judgment of experts in a field are systematically used to reach an agreement. In this context, following a literature review, an extended list (questionnaire) of 32 factors belonging to different SWOT categories was drawn up. The questionnaire was sent to six energy experts at universities in different EU countries, two energy experts at the Institute for Energy in two EU countries, and two experts from a Croatian government agency. The experts prioritized the factors in the questionnaire but asked to remain "anonymous". By summarizing the results of the questionnaire, a list of the 5 most important factors in each SWOT category was created.

The Analytic Hierarchy Process (AHP) was used to quantitatively determine the weighting coefficients of the identified influencing factors. This approach involves a modified Delphi method for determining the relative importance of the individual criteria. The hierarchy comprised four levels (Figure 1):

1. Goal: Optimal PSH deployment strategy.
2. Criteria: SWOT categories (S, W, O, T).
3. Subcriteria: 20 identified factors.
4. Alternatives: Critical factors.

At each level of the hierarchy, the criteria are compared in pairs based on their importance. Within the AHP framework, these pairwise comparisons utilize the standardized Saaty scale, which defines nine levels of importance as follows:

1: Equal importance.
3: Moderate importance.
5: High importance.
7: Very high importance.
9: Extreme importance.
2, 4, 6, 8: Intermediate values between the above levels.

$N\ (n-1)/2$ pairs of factors were compared, where n is the number of factors. For this purpose, we created a real matrix $n \times n$, denoted by A. Each entry of this matrix, a_{ij}, indicates how important the criterion i is in relation to j, so that $a_{ij} = 1/a_{ji}$ [26]. Matrix A is of the form

$$A = \left(a_{ij}\right)_{nxn} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \ddots & a_{2n} \\ \vdots & & \dots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (1)$$

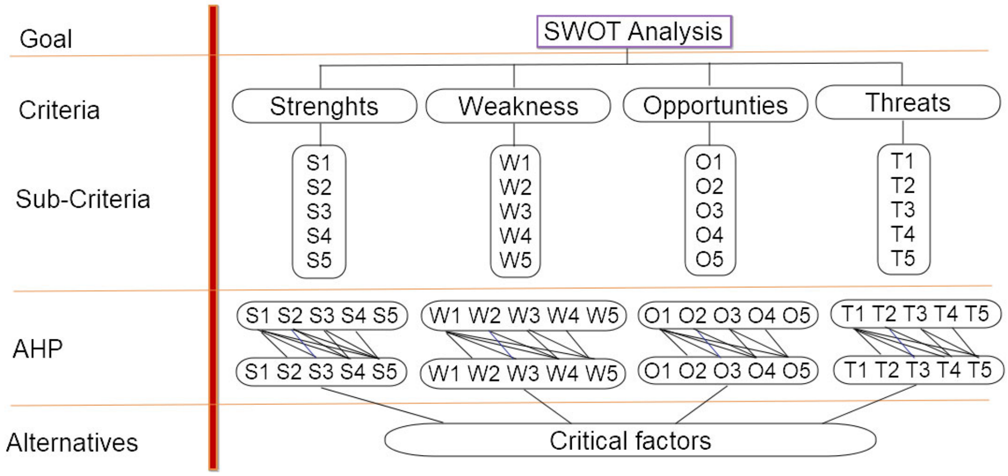


Figure 1. SWOT-AHP model for optimal PSH deployment strategy.

The normalized matrix was obtained from the matrix A. The n-dimensional column vector, denoted by W, represents the weighting vector (priority) for the compared factors and is determined by calculating the average of the entries in each row of the normalized matrix:

$$W_j = \frac{\sum_{l=1}^{n} \bar{a}_{lk}}{n} \quad (2)$$

where $\bar{a}_{lk}$ represents entries of the normalized matrix.

It is important to emphasize that the reliability of the AHP results depends directly on the consistency of the pairwise comparison judgments. If the pairwise comparisons are perfectly consistent, the matrix A reaches rank 1 and the maximum eigenvalue ($\lambda_{\max}$) is equal to the matrix size (n). In practical applications, however, it is extremely rare for perfect consistency to be achieved. Instead, the actual $\lambda_{\max}$ is calculated using the following formula:

$$\lambda_{max} = \frac{A \cdot w}{w} \quad (3)$$

The discrepancy between ideal and real consistency underlines the importance of calculating the consistency ratio (CR) to check the credibility of AHP results. There are several ways to calculate the CR. In our case, the linear fit proposed by Alonso and Lamata was used [27].

$$CR = \frac{\lambda_{max} - n}{2.7699 \cdot n - 4.3513 - n} \quad (4)$$

The generally accepted upper limit for CR is 0.1. If the final consistency ratio exceeds this value, the evaluation procedure must be repeated to improve consistency.

In the final phase, the overall priority vector is calculated by multiplying the local weightings of the factors by the specific group weighting to determine the priority ranking of the SWOT factors.

$$\text{Global Weight} = \text{Local Weight} \times \text{Category Weight} \quad (5)$$

So, as a result of process we obtained the following:

- Local weights: Factor prioritization within each SWOT category.
- Global weights: Cross-category prioritization.

AHP calculations can be performed with a spreadsheet, but in this case the online AHP calculator by Klaus Goepeepel [28] was used.

In this study, a model validation is carried out that includes a historical adjustment, an expert test, and a scenario test. Historical adjustment means that the model was calibrated using historical data on PSH capacity additions, policy incentives, and market conditions from 2015 to 2020. The model achieved an accuracy of over 90%. Expert test means that the Delphi technique was applied. Scenario test means that the model predicts 46% renewable energy integration by 2030 and 80% by 2050, which is broadly in line with IRENA's decarbonization targets.

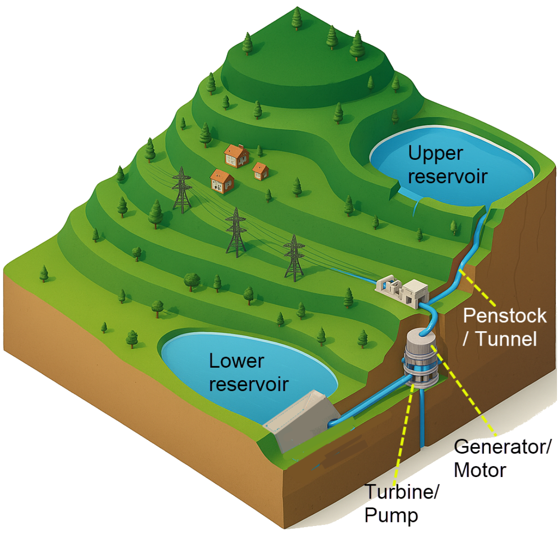
3. Results

3.1. Energy Storage Technologies

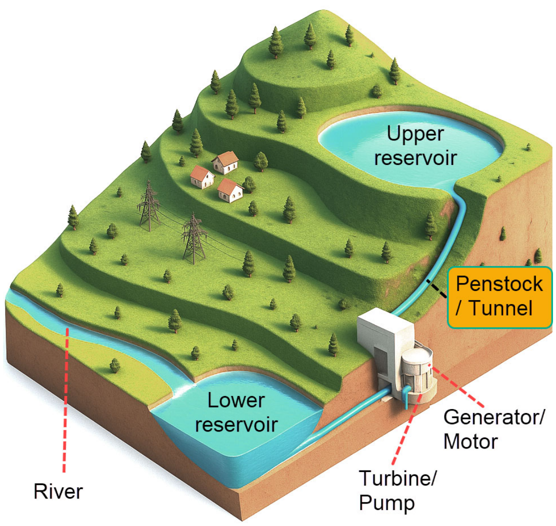
3.1.1. PSH Technology

Technical Characteristics

The PSH is a reversible mechanical energy storage system that uses the difference in height between two water reservoirs to convert the potential and kinetic energy of the water into electricity [29]. Worldwide, the PSH is one of the most cost-effective ways to store large amounts of energy in the long term [30]. In addition, due to its flexibility and generation capacity, it offers great potential for providing ancillary services and balancing power generation from a range of different energy sources [31]. There are various configurations of PSHs, the most common of which are open and closed systems, as shown in Figure 2.



(**a**) Closed-loop.



(**b**) Open-loop.

Figure 2. Closed-loop (**a**) and open-loop (**b**) PSH plants (source: own).

The open-loop configuration of a PSH is a system that is continuously connected to a natural body of water, with the lower reservoir at a lower elevation on a river (or at the sea [32]) and the upper reservoir at a higher geographical elevation. The PSH is located between the two reservoirs. In this configuration, water flows naturally from the upper reservoir to the lower reservoir, generating electricity in the PSH, while water is transported from the lower reservoir to the upper reservoir to store potential energy [31]. The closed-loop configuration consists of two artificial reservoirs outside the river courses. In a closed-loop system, all the water used for power generation comes from the previous pumping operation and there is no other natural water source (river) for the generation system [33]. Surface or groundwater can be used to initially fill the reservoir and then add water to compensate for evaporative losses [34]. According to Surabhi Karambelkar et al. [35], most of the existing pumped storage plants in the USA are open and located on natural water bodies. However, more than 80% of newly proposed projects are closed because they are located near natural water bodies and are said to have lower social and environmental impacts. This is also logical because most of the world's land area is not near rivers, so there are many more potential sites for closed power plants than for open power plants on rivers. There are different configurations of the machines used in PSHs. In the first configuration, special turbines, generators, and motor pumps are used for the production or pumping phase. The same hydraulic machine can work as a turbine and pump in the second configuration. In this context, the reversible Francis turbine is the predominant turbine technology. The second configuration is less expensive than the first [33]. Ternary PSHs are a special configuration in which the motor–generator is connected simultaneously and via the same shaft (and two couplings) to a separate hydraulic turbine and pump [36], eliminating the need for reverse rotation to switch between the power generation and pumping phases. Depending on the available head, the turbine can be a Francis or Pelton turbine. The pump is usually a single-stage or multi-stage centrifugal pump. Since the turbine and the pump use the same piping, the system can only operate in pumping or production mode at any given time. Among other advantages, the ternary PSH system has a better response time than the conventional PSH system, as it can switch more quickly between the production and pumping modes [22].

The main limitation of these systems is that they require specific geographical conditions, although alternative concepts such as the use of deep salt caves, the use of abandoned coal mines, or the construction of hollow bodies on the seabed are being considered [37,38].

Historical Development

The first PSHs appeared in the 1890s in the Alpine regions of Switzerland, Austria, and Italy and were originally intended for water management [30]. In 1929, the first pumped storage hydroelectric plant (PSH) in North America was installed on the Housatonic River in Connecticut [33]. Early designs used separate pump impellers and turbine generators. Since the 1950s, the predominant design has been a single reversible pump turbine [30]. A significant development of the PSH occurred in the 1960s when many countries began to consider the dominant role of nuclear power. Many PSH power plants were designed to supplement nuclear power to meet peak electricity demand [30,33]. According to the available data, the world's first reversible pump turbine was installed in 1937 at the Pedreira plant in Brazil. It had an output of 5.3 MW, a height of 30 m, and a rotation speed of 212 rpm [33]. There are also pumped storage hydropower plants in Croatia. The most important of these was the PSH Velebit, which was commissioned in 1984 with an output of 2 ×138 MW in generator mode and 2 × 120 MW in pumped storage mode [39]. In the 1990s, the construction of new pumped storage power plants (PSHs) declined, mainly due to increasing environmental concerns and a lack of suitable sites.

The first machines had a constant rotation speed, and in 1996 the first 395 MVA adjustable rotation speed machine at Ohkawachi PSH in Japan entered commercial operation. The first 30 MW seawater demonstration PSH was commissioned in 1999 as part of the Yanbaru project in the city of Okinawa, Japan [40]. However, there are significant environmental and engineering challenges that need to be overcome for this technology to be used more widely. The world's largest PSH is the Fengning power plant in China's Hebei Province, which was commissioned in late 2024. The power plant has 12 reversible pumped-turbine units, each with a capacity of 300 MW, including two variable-speed units, bringing the total installed capacity to 3.6 GW. It is designed to produce 6.61 TWh per year with the consumption of 8.71 TWh of electricity for pumping [41]. Today, China leads the global PSH market with an installed capacity of over 50.9 gigawatts (GW), followed by Japan with 21.8 GW, the USA with 16.7 GW, and Germany with 5.4 GW [42].

PSH systems were originally developed to manage the difference between the daily cycle of electricity demand and base load demand for coal and nuclear power plants: energy was used to pump water into the upper reservoir when electricity demand was low (typically at night, low electricity price), and the water was then transferred from the upper reservoir via a turbine to the lower reservoir to generate electricity during periods of the day when electricity demand was high (peak demand, high electricity price) [29]. In the last 10 years, interest in PSHs has increased due to the growing use of intermittent renewable energy. The provision of ancillary services such as balancing services, frequency stability, and black start illustrates the crucial role of PSHs in modern electricity grid management [29]. PSH technology has made dramatic advances in terms of reliability, efficiency, and generation capacity. Modern PSPs can switch from pumping to generating mode within minutes and operate at various partial load levels [43]. This brief historical overview of PSH systems demonstrates their importance and adaptability to the evolving needs and requirements of the electricity market over time.

Modern Trends and Innovations in PSH Technology

The most important trends in the development of PSH technology are as follows:

(a) Integration with renewable energy sources.

The PSH is increasingly being used to balance intermittent renewable energy sources such as wind and solar. The combination of the PSH with solar and wind energy makes it possible to balance intermittency. Studies show that hybridization reduces CO_2 emissions by 30–40% compared to fossil energy use [44,45]. The Spanish Alcántara II power plant combines floating solar plants with existing reservoirs, which lowers infrastructure costs and reduces evaporation losses. At the same time, the efficiency of the solar cells is increased by water cooling.

(b) Digitization and advanced management.

Modern monitoring and control systems are used to optimize operation and maintenance and improve efficiency. Digital twins and numerical modeling are used to optimize plant operation. AI-driven analysis helps to detect potential failures before they occur, reducing downtime and maintenance costs [44]. Real-time simulations make it possible to analyze the turbine load under changing loads [46]. Modern sensors and IoT devices collect real-time data on turbine performance, water flow, and grid conditions, enabling operators to dynamically optimize operations [47]. Digital and intelligent monitoring systems are being used more and more frequently. These include operational monitoring, real-time analysis of performance parameters, and fault diagnostics, which significantly improve the maintenance and operability of systems [48,49]. Digitalization also enables the automatic collection and processing of data on plant operation, which facilitates the creation of reports, analysis of key indicators, and faster strategic decision-making based on reliable and up-to-date information. Advanced and reliable measurement technologies are being developed, including miniaturized, smart, and networked sensors such as laser and fiber optic sensors, which have significant potential [48].

However, there are still technical bottlenecks, such as resonance problems under extreme operating conditions that cannot be detected and checked in time, and effective evaluation and application of monitoring data [50].

(c) Variable-speed turbine.

Variable-speed pump turbines offer several advantages over fixed-speed pump turbines for PSH projects, such as a wider operating range, higher efficiency, and dynamic power control in turbine and pump operation, allowing the system to respond much faster to fluctuations in renewable energy. With this technology, the rotor speed can be adapted to the current grid requirements, which increases energy efficiency by 4–15% depending on the operating conditions [51–53]. The use of doubly fed induction machines with frequency converters (DFIMs) enables continuous power regulation [52,54], ensures better control of the electrical machines during the start and stop phases, and increases the overall efficiency (up to 85%) [44,45]. Variable-speed turbines provide flexible ramping capacity, i.e., the ability of a generator to rapidly increase or decrease its output according to changes in the predicted net load. They have also enabled PSH turbines to reach full output in less than 30 s when connected to the grid.

(d) Innovation in turbine design.

New tools such as CFD are being used to model and numerically analyze water flow in Francis turbines, leading to improvements in design and performance [55,56] by analyzing the 3D flow in a water turbine using CFD simulations that provide assumptions for design improvements. In study [57], the 3D flow in a Francis turbine was analyzed, and the agreement with experimental results was confirmed.

Eddy current turbines and Alden turbines minimize the impact on aquatic ecosystems and reduce fish mortality by 90–98% [44]. For low-water sites, turbines with a minimum gap runner are currently being developed to increase efficiency at heads below 10 m [58]. The development of advanced materials that improve the performance and durability of PSH components should also be mentioned.

(e) Integration with unconventional accumulations.

The use of disused mines or underground tanks as reservoirs removes geographical restrictions. Research shows, for example, that seawater-based hydropower plants can be integrated into coastal areas [44].

(f) Modernization of existing facilities.

The modernization of the PSH increases storage capacity without the need to build new infrastructure. It also considerably extends the service life of PSH facilities. For example, plants in the USA that were modernized in the 2010s are still operating at an efficiency of 85% [48]. The implementation of advanced control and monitoring systems enables better integration with other parts of the energy system. For example, ref. [59] describes how dynamic models (e.g., Siemens PSS®E) have improved the management of grid flexibility. The WECC study shows a 22% reduction in curtailment of renewables through AS technologies [48]. The same study mentions the use of AI and IoT for real-time optimization of plant operation. The modernization of PSHs is part of a broader energy transition strategy that aims to increase the share of renewable energy and reduce CO_2 emissions. For example, ref. [60] states that PSHs will enable the integration of 46% of variable renewables into the grid by 2030. An IRENA report from 2020 [61] highlights that retrofitting a PSH reduces CO_2 emissions by 15–20% compared to new installations.

(g) Environmental sustainability.

The use of biologically permeable turbines and fish protection systems reduces the impact on aquatic ecosystems. In more recent projects such as the Iberdrola power plant in Spain, the entire water circuits are underground in order not to affect the landscape [44]. Modern modeling techniques help to control sedimentation and improve the longevity of the plants.

3.1.2. Other Energy Storage Technologies

Various key technologies are used in modern power grids to facilitate the storage and subsequent use of energy. Electrochemical systems, particularly battery systems, are among the fastest expanding types of grid-scale energy storage technologies, largely due to the rapid advances and decreasing costs of battery technology [62,63]. Lithium-ion batteries are leading the grid-scale battery storage market. In the United States, the electric grid includes approximately 10.6 GW of large-scale battery storage systems, primarily managed by grid balancing operators that utilize lithium-ion batteries for short-term storage averaging four hours and used to balance supply and demand in real time [64–66]. Lithium-ion batteries are ideal for short-term storage (up to 8 h), as high charge levels are associated with high costs and loss of quality. They offer high energy density, fast response times, and steadily decreasing prices, making them a compelling choice for grid-level applications such as frequency and voltage regulation [67].

Flow batteries offer longer-term energy storage [68]. They store energy in liquids in two separate tanks, which are pumped into a cell with electrodes when charging or discharging. The key advantage of flow batteries is that the amount of energy stored, which is determined by the tank size, can be adjusted independently of the output power, which is determined by the pump speed. Flow batteries are characterized by lower investment costs, a charging/discharging time of more than 4 h, and a long service life. However, they have a lower energy efficiency (60–80%) compared to lithium-ion batteries. In addition, flow batteries can withstand more than 10,000 charge/discharge cycles with minimal degradation, outperforming lithium-ion systems, which typically last less than 5000 cycles [69,70]. Sodium-ion batteries are less flammable and contain less expensive and critical materials, making them a potential alternative to lithium-ion batteries. Although they have a lower energy density and possibly a shorter lifespan, they could be 20–30% cheaper if produced on the same scale as lithium-ion batteries [71,72].

CAES (compressed air energy storage) uses underground cavities to store compressed air, which drives turbines to generate electricity when needed [68,69]. Advanced CAES can achieve an efficiency of around 75% [73], with the largest plant in China offering 300 MW of power and 1500 MWh of capacity at an efficiency of around 70% [74]. Flywheel systems store energy in the form of kinetic energy in a rotating mass. They deliver up to 30 kW/kg and release 80% of the stored energy in less than a second [75], with magnetically levitated flywheels achieving 95% efficiency [76]. However, flywheels are still more expensive than batteries, and supercapacitors and are not used on a large scale [77].

Electrical/electromagnetic energy storage systems include supercapacitors and superconducting magnetic energy storage systems. Supercapacitors are ideal for applications that require high power for short periods. Thanks to their high power density and fast response time (less than 1 s), they are used in the power grid to regulate frequency and voltage [78,79].

Thermal energy storage systems, such as Carnot batteries, store electricity in the form of heat and convert it again using thermodynamic cycles [80]. Although they are less efficient than pumped storage power plants or batteries, their capital costs can be 20–30% lower for storage times of more than 8 h [81].

Chemical energy storage includes hydrogen, synthetic natural gas, and ammonia for long-term storage. Hydrogen can be converted to methane (via the Sabatier reaction, ~80% efficiency [82]) or ammonia (via the Haber–Bosch process [83]). Storing hydrogen in salt caverns costs about 0.6 USD/kWh, while the capital costs for storing liquid ammonia are 5 to 10 times lower than for hydrogen [84]. The Klar study [85] shows that long-term storage (e.g., hydrogen or thermal batteries) has an LCOS >500 USD/MWh, making it uncompetitive without subsidies.

3.2. Key Technical Aspects of PSHs and BESSs

BESSs and PSHs are complementary pillars of modern energy storage. Although they are often seen as competing technologies, their synergy enables optimal integration of renewable energy sources. Tables 1 and 2 compare the most important technical aspects of BESSs and PSHs [86–90].

Table 1. Key technical aspects of batteries and PSHs.

Parameter	BESS (Li-ion)	PSH
Storage capacity	Typically up to 100 MWh per system	Up to 10+ GWh per plant
Energy capacity	2–4 h daily (typically)	6–8 h daily
Efficiency	80–88% (with inverters)	75–80%
Response time	<1 s	2–5 min
Lifespan	10–15 years	80–100+ years
Degradation	2–3% by year	Negligible

Mauro et al. state that modern PSHs achieve efficiencies of 70% to 85% when losses due to evaporation of stored water and losses due to energy conversion are taken into account [30,51]. PSHs can respond quickly to fluctuations in demand, usually within seconds to minutes [61,91,92].

Table 2. Efficiency and energy losses.

Parameter	BESS	PSH	Source
Round-trip efficiency	85–90%	75–80%	[61,92,93]
Impact on LCOS	Lower energy losses	Higher losses require additional production	

PSH: Losses of 20–25% per cycle require more energy to compensate [93].

In terms of implementation flexibility, BESSs offer a modular design and can be installed in urban locations. In contrast, PSHs require specific geomorphological conditions and a sufficient height difference to be feasible (implementation aspects).

When considering the impact on the electrical network, PSHs inherently provide rotational inertia, which helps ensure network stability. BESSs, on the other hand, are superior for managing rapid fluctuations in grid frequency. For the integration of renewable energy sources (RES), the PSH is more efficient for seasonal energy storage.

3.3. Key Economic Aspects of PSHs and BESSs

The levelized cost of electricity storage (LCOS) is defined by Schmidt et al. [94] as the total cost of electricity storage over the lifetime of the system, expressed in a currency per unit of energy released (e.g., USD/MWh). This method includes capital costs (CAPEX), operating costs (OPEX), charging costs, and technological degradation and replacement costs. The study [63] analyzes the cost components of LCOS in detail. The study [95] points out that systems such as supercapacitors or flywheels have lower LCOS (~200 USD/MWh) for short-term applications due to the high cycle frequency (>10,000 per year). For Li-ion batteries, according to studies by NREL [96] and PNNL [92], the LCOS values are between 260 and 330 USD/MWh, while according to [97], a 100 MW (without subsidies), 4 h LCOS system (400 MWh) in the USA in 2024 is in the range of 170 to 296 USD/MWh. Klar [85] points out that long-term storage systems (e.g., hydrogen or heat batteries) have a low cycle frequency (<100 per year) and high capital costs with LCOS >500 USD/MWh. According to the analysis by Mulder and Klein [95], the LCOS is most dependent on the capital costs, the number of cycles, and the discount rate. A 30% reduction in CAPEX, for example, reduces the LCOS by 20–25%.

According to the study by Schmidt et al. [94], a similar indicator to the LCOS is the annualized capacity cost (ACC), which is lowest for systems with a low number of cycles (less than 300 per year) and a short discharge time (less than one hour). This analysis shows that systems with high power density and fast response but relatively low energy capacity are best suited for applications such as auxiliary services or black start. Ziegler & Trancik [98] point out that prices for lithium-ion batteries have fallen by 97% since 1991, with an average annual rate of 13%. An overview of demand and costs in the vanadium redox flow battery (VRFB) market [99] shows that doubling the global capacity of vanadium redox flow batteries could reduce production costs by ~10–15% through economies of scale and supply chain optimization. Böhm et al. [100] analyzed the learning rates for different components of hydrogen electrolysis systems, including alkaline and PEM electrolyzers. The authors reported learning rates between 9% and 30% for the different components, with an average rate of about 18% for the overall systems.

According to Thunder Said Energy [101], vanadium flow batteries require a difference of 0.15–0.20 USD/kWh in storage costs to be competitive with lithium-ion batteries. Although the learning rate is lower than for lithium-ion batteries (~14% vs. ~19%), the long lifetime (>20 years) compensates for the higher initial costs The IRENA report [102] documents that PSH systems have not shown significant cost reductions due to technological maturity and geographical limitations. Capital costs remain stable (~60 USD/kWh) despite the increase in installed capacity. Menéndez et al. [103] point out that underground PSHs have an efficiency of 75–85% but require high initial investment due to geological challenges. Mongird et al. [104] confirm that the costs of PSHs are primarily determined by site-specific conditions (e.g., geology, water column) and not by production experience.

In grid systems with less than 40% variable renewables, only short-term storage (less than 4 h) is required for their integration [105]. When the share of variable renewables exceeds 60%, flexibility becomes essential. Technologies such as compressed air energy storage (CAES) or flow batteries have become economically viable in compensating for daily and weekly fluctuations, with a storage duration of between 4 and 16 h [106].

Economic aspects include fixed operating costs, variable operating costs, and lifespan and long-term costs (see Tables 3–6). PSH requires 2–3 times higher initial investment per MW [104].

Table 3. Fixed operating costs (O&M).

Parameter	BESS (Li-Ion)	PSH	Source
Fixed O&M	6–8 USD/kW-per year	2.5–5 USD/kW-per year	[92,96] vs. [93]
Explanation	Include monitoring, software, and periodic maintenance costs, spare parts, and labor	Lower due to less need to replace components	

Table 4. Variable operating costs.

Parameter	BESS	PSH	Source
Variable O&M	0.1–0.3 USD/MWh	0.5–1 USD/MWh	[92,93]
Explanation	Almost negligible (no moving parts)	Maintenance costs of turbines, pumps, and water losses due to evaporation	

- BESSs: These must be completely replaced after 10–15 years, which increases the LCOS [92].
- PSH: Mongird et al. [104] point out that the main maintenance costs are related to the rotating equipment (turbines), which are replaced every 30–40 years.

Table 5. Lifespan and long-term costs.

Parameter	BESS	PSH	Source
Lifespan	10–15 years	50–80+ years	[61,92,93]
Replacement costs	High (entire system)	Low (partial overhauls)	

Table 6. Levelized cost of storage (LCOS).

Type	Parameter	Value (2024)	Source
BESS (lithium-ion batteries)	LCOS (4 h system)	0.296 USD/kWh	[97]
	LCOS (10 h system)	0.170 USD/kWh	[97]
	Trends	Reduction of 30–40% by 2030	[96]
PSH (Pumped storage hydropower)	LCOS (10 h system)	0.05–0.15 EUR/kWh	[107]
	LCOS (24 h system)	0.03–0.10 USD/kWh	[92]
	Trends	Stable costs until 2050	[61]

According to the Table 6, PSHs have significantly lower LCOS than BESSs for long-term storage (>10 h) due to their longer lifetime (80+ years) and low operating costs. The main costs of PSHs are related to the construction of the infrastructure (reservoirs, turbines), but in the long term they are cost-efficient. The construction time for BESSs is typically between 12 and 18 months, whereas PSH projects require significantly longer, usually between 5 and 8 years.

3.4. Key Ecological Aspects of PSHs and BESSs

From an ecological perspective, CO_2 emissions are a very important environmental consideration. Table 7 provides a comparison of CO_2 emissions for BESS and PSH systems.

Table 7. CO_2 emissions (gCO_2/kWh).

Phase	BESS	PSH
Component creation phase	150–200	20–30
Phase of system operation	0	0
End-of-life phase	50–70	N/A

PSH projects can increase soil erosion and degradation as well as seismicity and subsidence due to excavation and tunneling during construction and the use of groundwater pumping during operation [34]. The clearing of vegetation and flooding of land can lead to habitat fragmentation or loss [108]. BESSs have significant environmental issues associated with lithium mining and recycling [109–111].

The features mentioned above and the literature show important advantages and disadvantages of the individual technologies. The advantages of BESSs lie in their fast response and modularity, which enable precise voltage/frequency regulation and mitigate the fluctuations of solar and wind energy through short-term storage. They can be used in urban areas without geographical restrictions and offer the possibility of modular scaling of capacity.

The disadvantages of BESSs include limited energy density, which means that large areas are required for capacities of more than 100 MWh; material wear and loss of capacity over time; the environmental impact of lithium and cobalt; and the safety risk of thermal failure of lithium-ion batteries.

The advantages of PSHs are the lowest LCOE among large-scale storage technologies, a long lifetime, and a global warming potential (GWP) that is 2–5 times lower for closed PSH systems than for lithium-ion batteries [20,21].

The disadvantages of PSHs are geographical limitations, high investment costs, a long development cycle, and potential impacts on habitats.

3.5. SWOT-AHP Analysis

A SWOT-AHP analysis was carried out to assess the prospects of PSH technology. The combination of SWOT and AHP methodologies enables a structured assessment of the most important factors influencing the development of PSH technology.

In the following, the factors for the main categories of the SWOT analysis (strengths, weaknesses, opportunities, and threats), which were already analyzed previously, are first defined. For each category, the five most influential factors are selected and briefly explained.

3.5.1. Main Strength of PSH

Pumped storage hydropower plants have five main strengths (S):

S1: Mature technology with high efficiency (80–90%).

S2: High flexibility and grid stabilization.

S3: Long service life (around 60 years).

S4: Energy storage capacity in reservoirs.

S5: Possibility of multi-purpose use of the tank.

S1: The efficiency of pumped storage hydropower plants reaches 80–95% depending on the size of the plant, which was proven by studies by [112]. The high degree of energy conversion is the result of the optimization of the turbine design and the reduction of friction losses in the system [112].

S2: PSH systems provide real-time frequency regulation and support the integration of variable renewable energy sources (VRES), as analyzed in the study by Simão and Ramos [18]. For example, variable turbines allow power adjustment in pumping and generation modes, ensuring a balance between supply and demand [112,113].

S3: A study by Simon et al. [20] on the life cycle of closed PSH systems confirms that the average service life with maintenance is 80 years, possibly extending to 100 years. This longevity is due to the robust construction of concrete dams and corrosion-resistant materials [20].

S4: According to an analysis by Hunt et al. [114], seasonal pumped storage hydropower plants can store up to 17.325 TWh of energy worldwide, which corresponds to 79% of global electricity consumption in 2017. Hybrid systems with batteries and PSHs reduce dependence on fossil sources [115–117].

S5: PSH reservoirs are used for irrigation, flood control, and recreation, as highlighted in a study by Hunt et al. [114]. For example, hybrid projects combine PSHs with floating solar power plants, reducing infrastructure costs [118].

3.5.2. Main Weakness of PSH

Pumped storage hydropower plants have five major weaknesses:

W1: Environmental and social impacts associated with construction.

W2: Dependence on topographical conditions.

W3: High investment costs.

W4: Complexity of the approval process.

W5: Efficiency losses (energy losses during the pumping and generation cycle, typically around 20%).

W1: A study on the impacts of dams in Burundi [29] found that the construction of reservoirs leads to the displacement of communities, the destruction of agricultural land, and the fragmentation of river ecosystems. For example, the use of explosives in the construction of tunnels leads to air and soil pollution. In the case of the Grand Coulee Dam

(USA), a study [119] shows permanent changes in the lives of indigenous communities and the loss of cultural heritage.

W2: According to the analysis of Hunt et al. [114], seasonal PSH systems require a minimum hydraulic head of 50 m and proximity to a river with sufficient flow. Only 1.2% of the world's land area fulfills these conditions, which limits implementation to mountainous regions. Topographical constraints also increase the cost of building tunnels and dams.

W3: An economic analysis of the Turkish PSH project [120] shows that the investment costs are a major factor in the unprofitability of the project. Construction costs vary between 1500 and 2500 USD/kW, with a payback period of 9 to 28 years, depending on market prices for energy. Battery systems have lower initial costs (~600 USD/kW).

W4: A study by the National Hydropower Association [121] shows that the approval process takes 2–3 times longer than for solar or wind power plants. For closed PSH power plants, the impact on groundwater, geological stability, and species migration must be assessed, which lengthens the administrative process.

W5: Antal [122] showed in his analysis that the total losses in the pumping and generation cycle amount to 20–35%. The leading causes are the friction in the pipelines (2–3%), the non-optimal efficiency of the pumps, and the losses of the transformers (1–2%). These weaknesses require the integration of compensatory measures, such as hybridization with solar systems or the use of advanced materials to reduce friction. Although they are not directly related to the efficiency of the PSH, we should not forget the evaporative losses of water from the reservoir. It is also worth mentioning here the possible reduction in storage capacity (mainly in the upper reservoir) due to sedimentation. This reduction in capacity may limit the amount of water available for pumping and electricity generation, potentially affecting the overall efficiency and lifetime of the PSH plant [122,123].

3.5.3. Main Opportunities of PSH

Pumped storage hydropower offer five important opportunities (O):

O1: Increased need for energy storage due to the growth of renewables.

O2: Integration with other renewables (especially wind).

O3: Modernization of existing hydropower plants and hybridization.

O4: Strategic location in areas where grid regulation is required.

O5: Diverse revenue streams from various services.

O1: The share of variable renewable energy sources in global electricity generation is growing rapidly: from around 5% in 2015 to 9% in 2020 and to around 14% in 2024. This share is expected to reach 30% by the end of the decade [124,125]. According to the analysis by Hargreaves (2020) [4], systems with a high share of renewable energy sources (RES) require long-term energy storage to compensate for seasonal and multi-week solar and wind energy shortages.

O2: Research by Awan et al. [126] analyzed the synergy of wind and hydropower in Pakistan, where coordination reduces energy losses by 12–15% through shared infrastructure. For example, wind farms reduce the need for pumping at night, optimizing the operation of hydropower plants [126]. In a study by Schleifer et al. [115], hybrid PV–wind–hydro systems were found to increase grid stability by 20–30%.

O3: According to Schleifer et al. (2023) [115], the modernization of existing hydropower plants (e.g., digitalization, improvement of turbine efficiency) can increase annual production in the EU by 8.4%. Hybridization with floating solar systems reduces water evaporation by 30% while increasing production capacity [115,127]. A study by Nasir et al. [128] shows that hybrid projects can reduce infrastructure costs by 25% and LCOS by 28%.

O4: The analysis by Hargreaves (2020) [4] emphasizes that hydropower plants in mountainous regions (e.g., Alps, Himalayas) enable real-time frequency regulation and thus reduce the need for gas-fired power plants. In Sweden and Norway, hydropower plants cover 70% of grid-balancing services [129]. A study by Stocks et al. (2021) [130] identified 616,000 potential PSH sites outside the boundaries of protected areas and urban areas worldwide. These sites have an enormous total potential of 23,000 TWh, which is several orders of magnitude greater than would be required for a large-scale feed-in of wind and solar energy into the electricity grid. The sites are widely distributed around the world, and the capital costs vary from site to site.

O5: According to IRENA (2012) [117], hydropower plants in the USA generate 40% of their revenues from grid stability services (regulation, reserves). A study by the Oak Ridge National Laboratory [131] shows that hydropower plants generate 1346 USD/MWh revenues during peak periods through dynamic price management. Multi-service hybrid systems increase ROI by 25–30% [132,133]. These opportunities underline the importance of pumped storage hydropower for the transition to sustainable grids and the need for innovative financing models and regulatory frameworks.

3.5.4. Main Threats of PSH

Pumped storage hydropower plants are exposed to five main threats (T):

T1: Regulatory and market uncertainties.

T2: Financial inequality.

T3: Public opposition and long planning times.

T4: Development of alternative energy storage technologies.

T5: Climate change with impacts on water availability.

T1: Lengthy approval procedures (5–10 years) combined with environmental impact assessments increase the investment risk, according to a study by the National Hydropower Association (NHA) [121]. The average planning time for new PSH plants in the EU is 8–12 years, which is twice as long as for solar projects [121,134]. The lack of capacity markets in the EU prevents proper valuation of grid stability services, undermining projects' financial viability [135,136]. Unregulated competition between battery systems and PSHs leads to unequal support conditions, as an analysis of the Italian and Spanish markets shows [136]. Investors need the confidence that governments can give them by designing electricity markets with flexibility in mind and ensuring long-term revenue security [91].

T2: Financial inequality refers to the disparity in access to incentives, market mechanisms, and capital compared to other energy storage technologies. Capital costs (1500–2500 USD/kW) are 3–4 times higher than for lithium-ion batteries (~600 USD/kW), which limits investment [137]. Unlike solar/wind power plants, PSH projects do not have systematic tax breaks or subsidies in most markets. PSH provides grid stabilization services (e.g., frequency control), but markets often do not assign a value to these services, reducing ROI [138].

T3: Protests by indigenous communities (e.g., the Goldendale project in Washington) slow down construction due to concerns about the destruction of cultural heritage and environmental damage [135]. Conflicts over water use in Germany and Poland restrict PSH development as they compete with agriculture and drinking water, according to a Joint Research Centre analysis [134]. These threats require innovative approaches to risk management, such as hybridization with renewable sources or the use of closed PSH systems with minimal environmental impact [139].

T4: Lithium-ion batteries achieve lower costs (~600 USD/kW) and greater flexibility in short-term storage [135,140] and are increasingly competing with PSHs. Compressed air energy storage (CAES) and redox batteries are reaching specific costs of 600–2250 USD/kW, accelerating technology development [141]. According to an NREL report [135], markets do not recognize the full value of the flexibility of PSH systems compared to more advanced technologies.

T5: The decline in snow cover in mountainous regions (e.g., in the Himalayas) reduces the flow rate of rivers by 15–30%, directly impacting hydropower plants [136]. Droughts in the western USA (2012–2022) led to a 40% decrease in hydropower generation, highlighted in analyses by Oak Ridge National Laboratory [134]. Szinai et al. [136] point out that the hydropower potential in Europe will decrease by 23% by 2050 due to changes in hydrological cycles. Irregular precipitation patterns disrupt the predictability of reservoir filling, reducing the efficiency of PSHs by 15–20% in regions such as the Mediterranean [138].

3.5.5. Pairwise Comparison Matrix for Main SWOT Categories

The pairwise comparison matrix as well as the global weights (GPs) are listed below (Tables 8 and 9).

Table 8. Decision matrix for major categories.

	S	W	O	T
S	1	3	1	1/2
W	1/3	1	1/2	1/4
O	1	2	1	1/2
T	2	4	2	1

Table 9. The resulting main category weights.

	Category	Priority	Rank	(+)	(−)
1	Strengths (S)	24.37%	2	3.7%	3.7%
2	Weaknesses (W)	9.94%	4	1.3%	1.3%
3	Opportunities (O)	21.90%	3	1.8%	1.8%
4	Threats (T)	43.79%	1	3.7%	3.7%

Consistency check: λ_{max} = 4.021, CR = 0.008 (<0.1 → acceptable).

3.5.6. Comparison of Pairs Within Each SWOT Category

The pairwise comparison matrixes as well as the local subcategory weights (LSW) and the global subcategory weights (GSW) are listed below (Tables 10–12).

Table 10. Decision matrixes for internal factors (strengths and weaknesses subcategories).

	S1	S2	S3	S4	S5		W1	W2	W3	W4	W5
S1	1	1/2	2	1/3	2	W1	1	2	1/3	1	1/2
S2	2	1	3	1/2	3	W2	1/2	1	1/5	1/2	1/3
S3	1/2	1/3	1	1/4	1	W3	3	5	1	3	2
S4	3	2	4	1	4	W4	1	2	1/3	1	1/2
S5	1/2	1/3	1	1/4	1	W5	2	3	1/2	2	1

Table 11. Decision matrixes for internal factors (opportunities and threats subcategories).

	O1	O2	O3	O4	O5		T1	T2	T3	T4	T5
O1	1	3	5	2	3	T1	1	1	2	2	4
O2	1/3	1	2	1/2	1	T2	1	1	2	2	3
O3	1/5	1/2	1	1/4	1/2	T3	1/2	1/2	1	1	1
O4	1/2	2	4	1	2	T4	1/2	1/2	1	1	1
O5	1/3	1	2	1/2	1	T5	1/4	1/3	1	1/3	1

Table 12. Local and global subcategory weights.

Category	Consistency Ratio	Category Weights	Subcategory	LSW	GSW
Strength (S)	CR = 0.0080	0.2437	S1	0.1529	0.0373
			S2	0.2573	0.0627
			S3	0.0876	0.0213
			S4	0.4147	0.1011
			S5	0.0876	0.0213
Weakness (W)	CR = 0.00384	0.0994	W1	0.1350	0.0134
			W2	0.0743	0.0074
			W3	0.4143	0.0412
			W4	0.1350	0.0134
			W5	0.2415	0.0240
Opportunity (O)	CR = 0.00405	0.2190	O1	0.4112	0.0901
			O2	0.1333	0.0292
			O3	0.0694	0.0152
			O4	0.2529	0.0554
			O5	0.1333	0.0292
Threat (T)	CR = 0.0234	0.4379	T1	0.3092	0.1354
			T2	0.2916	0.1277
			T3	0.1370	0.0600
			T4	0.1722	0.0754
			T5	0.0899	0.0394

Since CR < 0.1 for all categories, we can conclude that the pairwise comparison matrixes are consistent, i.e., the estimates of the relative importance of the subcategories agree with each other.

4. Discussion

The application of the SWOT-AHP method in this study provides a structured, quantitative framework for the prioritization of strategic measures and thus goes beyond the qualitative assessments that traditionally predominate in this area. By quantifying the relative importance of strengths, weaknesses, opportunities, and threats, the analysis provides actionable insights for both policymakers and investors. The analysis revealed that the six most important global weighting coefficients are as follows:

T1: Regulatory and market uncertainties (13.54%).
T2: Financial inequality (12.77%).
S4: Energy storage capacity (10.11%).
O1: Increased need for energy storage (9.01%).
T4: Development of alternative energy storage technologies (7.74%).
S2: High flexibility and grid stabilization (6.27%).

Threats represent the most important SWOT category. The identification of regulatory and market uncertainties (T1) as the most important threat to the implementation of reversible hydropower plants (PSHs) is strongly supported by the broader energy storage literature. This factor is cited as the main reason for discouraging investment in energy storage technologies. This uncertainty applies not only to PSHs but also to other energy storage solutions at the grid level. Regulatory and market uncertainties (T1) reflect the challenges posed by evolving and sometimes unclear regulatory and market conditions that impact energy storage investment and deployment. Regulatory uncertainties include changing guidelines, inconsistent regulations across regions, and unclear classifications of energy storage, which can increase risk for investors and developers. In the USA, for example, investment decisions are made through a patchwork of regulations at the federal, state, and regional levels, while in Europe the regulatory framework for energy storage systems is even more complex.

This study's finding that financial inequality (T2) is a major threat is in line with a growing body of research highlighting the uneven distribution of incentives and capital in the energy storage sector. PSH projects, with their high initial costs and long payback periods, often struggle to compete for investment in technologies that benefit from more generous or better targeted subsidies. This mismatch is exacerbated in markets where policy mechanisms do not recognize the wider systemic benefits of PSHs, such as grid stability, inertia, and long-term storage, leading to underinvestment in these assets. Recent policy analyses highlight the need for equity-oriented incentive structures that recognize the unique value of PSHs and ensure that financial support is not disproportionately allocated to technologies favored by short-term market trends [142].

The benefits of PSHs highlighted in this study—particularly their large energy storage capacity (S4), long lifetime, and ability to stabilize the grid—continue to be strongly supported in the literature. Their ability to provide ancillary services, such as frequency regulation and zero-start capability, is increasingly recognized as essential for grids with a high share of variable renewable energy (VRE).

A significant advance highlighted in both this study and recent external research is the trend towards hybridization—the integration of PSHs with other renewable energy sources and green hydrogen production [143]. Papathanasiou et al. [143], for example, suggest the optimal size of a PSH in combination with grid-connected solar and wind energy in order to reduce the levelized cost of electricity (LCOE). Hybrid systems solve the problem of volatility of renewable energy sources, increase grid stability, and open up new revenue streams, making them attractive to both investors and policymakers. While BESS technologies are expanding rapidly, especially in markets with high flexibility needs and short-term storage requirements, PSHs continue to have a clear advantage in terms of scale, cost per unit of energy stored over longer periods, and life-cycle emissions. However, the annual expansion of stationary batteries is overtaking PSHs due to falling costs and shorter deployment times. This dynamic underline the importance of a policy framework that recognizes the complementary role of the two technologies.

The results emphasize the urgent need for policy reform. Simplified permits, standardized environmental guidelines, and targeted financial incentives are key to unlocking the full potential of PSHs. In addition, as the market develops, mechanisms that reward flexibility, resilience, and system-wide benefits, rather than just the lowest initial cost, will be critical.

In summary, the results of this study fit well into the broader academic discourse and highlight both the enduring value and changing challenges of pumped storage in the context of the global energy transition.

Future research should further refine SWOT-AHP methodologies, including dynamic modeling and scenario analysis, to capture the changing interplay between technology, policy, and market forces.

4.1. Application Predictions by 2030

Our main prediction is based on previously given data.

Global capacity: A significant increase in PSH capacity is expected worldwide, with a focus on integration with renewable energy sources. According to the IEA [144], 40 GW of new hydro capacity is needed annually to reach the target production of 5400 TWh.

Technological progress: Development of more efficient pumps and turbines and digitalization of energy management is needed. Digitalization enables faster and more precise adaptation of PSH system operations to changes in the electricity market and grid demand, including the integration of renewable energy sources.

Ecological design: In the near future, there will be more environmentally friendly projects and a reduction in negative environmental impacts [145]. A large number of new projects (70%) will combine solar and wind energy to increase the efficiency of land use.

Priorities: These include integration with green hydrogen (e.g., British Hydrogen Net Zero Investment Roadmap) [146] and digitalization of operations to optimize flexibility (IRENA highlights the potential for +15% efficiency) [61], as well as AI-driven reservoir optimization boosting efficiency by 8–12%.

4.2. Application Predictions by 2050

The key role of PSHs: According to IRENA, it is necessary to double the capacity of PSHs to enable the integration of 80% of renewable energy into the grids [147]. This expansion is essential for long-term energy storage and grid stabilization, which are critical in high-renewable scenarios.

Technological progress predictions are as follows:

- Variable turbines with variable rotation speed (+20% of operating range) [61].
- Combination with floating solar power plants (e.g., pilot project in Portugal) [61].
- Hybrid systems: Integration with green hydrogen for extended storage duration.
- Use of new, improved materials for PSH components.
- Digital optimization: the application of artificial intelligence and machine learning will increase operational efficiency.
- Environmental aspects highlight estimated emission savings of 355,000 tons of CO_2 per year per plant [148].

This projection positions the PSH as an essential element of a decarbonized network, requiring close collaboration between policymakers and industry.

5. Conclusions

This study analyzes the importance and prospects of using pumped storage hydro (PSH) in transforming the energy system on a global scale and increasing the share of renewable energy sources, with a focus on PSHs and battery energy storage systems (BESS) as the dominant options. This study reveals several important findings: The PSH is currently the largest form of energy storage on the grid, with a global capacity of 182 GW in 2023, although battery systems, especially lithium-ion batteries, are showing the fastest growth. Technological advances in PSHs include improvements in turbine design, the introduction of variable speed machines, the application of digital technologies to optimize operations, and the use of better materials for PSH components. An integrated economic–ecological analysis shows that the PSH has a 65% lower levelized cost of energy (LCOE) and five times lower emissions compared to the BESS.

By applying a SWOT-AHP analysis for the strategic categorization of influencing factors, this study shows that regulatory uncertainty (35%) and capital expenditure (CAPEX, 25%) are the biggest barriers to wider adoption.

The increased need for energy storage and the high flexibility of PSHs are recognized as the main advantages. Forecasts up to 2050 show that PSH capacity will need to double to enable the integration of 80% renewable energy sources into the grid.

Recommendations for policymakers include the development of clear, accelerated approval procedures and standardized environmental guidelines to reduce project delays and uncertainty. It is also important to introduce mechanisms to reduce financial risk, such as subsidies covering 20–30% of project capital costs, low-interest loans, and the introduction of revenue stabilization measures, such as capacity auctions. In addition, incentives for hybridization should be created by funding research and development for the joint use of PSHs and green hydrogen to improve seasonal storage and supporting the introduction of digital twins for operational optimization. It is recommended to revise grid legislation to require off-grid commissioning and frequency regulation as a prerequisite for the provision of grid service provision and to position the PSH as an important resource for resilience. Finally, fostering public–private collaboration is critical to address supply chain bottlenecks and local stakeholder concerns and ensure sustainable and socially responsible deployment.

These measures would mitigate the primary threats identified in our SWOT-AHP analysis, accelerating the implementation of the PSH to meet IRENA's net-zero emission targets.

Author Contributions: Conceptualization, M.B.; methodology, M.B.; validation, M.B. and S.M.; formal analysis, N.V.; investigation, M.B. and N.V.; resources, M.B. and J.T.B.; writing—original draft preparation, M.B. and N.V.; writing—review and editing, J.T.B. and S.M.; visualization, M.B.; project administration, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is available on the reasonable request sent to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ACC	Annualized Capacity Cost
AHP	Analytic Hierarchy Process
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CI	Consistency Index
CO_2	Carbon Dioxide
CR	Consistency Ratio
CSP	Concentrated Solar Power
DFIM	Doubly Fed Induction Machine
GHG	Greenhouse Gas
GSWs	Global Subcategory Weights
GWP	Global Warming Potential
IEA	International Energy Agency
IoT	Internet of Things
IRENA	International Renewable Energy Agency
LCOS	Levelized Cost of Storage
LCOE	Levelized Cost of Energy
Li-ion	Lithium-Ion
LSWs	Local Subcategory Weights
NHA	National Hydropower Association
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditure
PSH	Pumped-Storage Hydropower
PV	Photovoltaic
ROI	Return on Investment
SWOT	Strengths, Weaknesses, Opportunities, Threats
VRES	Variable Renewable Energy Sources
VRFB	Vanadium Redox Flow Battery

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