

Pumped-Storage Hydroelectric Plants with Pressurized Reservoir Replacing the Upper Reservoir

Usinas Hidrelétricas Reversíveis com Reservatório Pressurizado Substituindo o Reservatório Superior

Article Info:

Editor handled this article: **Ibrahim Ademola Fetuga**

Article history: Received 2026-07-25 / Accepted 2026-09-20 / Available online 2026-10-07

doi: [10.18540/jcecv112iss1pp24709](https://doi.org/10.18540/jcecv112iss1pp24709)

Mateus Borel Calegario Miguel

ORCID: <https://orcid.org/0009-0000-0037-9637>

Universidade Federal de Viçosa, Brazil

Email: mateus.miguel@ufv.br

Henrique Marcio Pereira Rosa

ORCID: <https://orcid.org/0000-0002-1437-2265>

Universidade Federal de Viçosa, Brazil

Email: henrique.rosa@ufv.br

Rogério Fernandes Brito

ORCID: <https://orcid.org/0000-0002-6833-7801>

Universidade Federal de Itajubá, Brazil

Email: rogbrito@unifei.edu.br

Charles Luis da Silva

ORCID: <https://orcid.org/0000-0003-1558-0485>

Universidade Federal de Viçosa, Brazil

Email: charles.silva@ufv.br

Álvaro Messias Bigonha Tibiriça

ORCID: <https://orcid.org/0000-0002-3300-1988>

Universidade Federal de Viçosa, Brazil

Email: alvaro.tibirica@ufv.br

Paulo Cezar Büchner

ORCID: <https://orcid.org/0000-0001-7373-3705>

Universidade Federal de Viçosa, Brazil

Email: paulo.buchner@ufv.br

Abstract

The growing share of intermittent sources, such as solar and wind power, in the electricity mix has heightened the need for storage systems capable of mitigating fluctuations in supply and ensuring energy security. Among the available technologies, pumped-storage hydropower (PSH) plants stand out; they store energy by pumping water to an elevated reservoir, allowing it to be used later for electricity generation. However, topographical and environmental constraints can limit their implementation. In this context, this study proposed an alternative storage system based on the principles of pumped-storage hydroelectric plants, in which the upper reservoir is replaced by a pressurized reservoir. In this configuration, energy is stored through the compression of the air confined within the reservoir. The study involved mathematical modeling of the pumping and turbine stages, followed by computational simulation using the Python programming language. The results made it possible to analyze the temporal evolution of operational variables and to evaluate the efficiency of the proposed system, showing that the system, in its current configuration,

exhibited lower efficiency than conventional pumped-storage hydroelectric plants. Thus, this research presents the concept of the system and establishes a foundation for future studies.

Keywords: Energy Storage. Pumping. Turbine. Electricity Generation.

Resumo

O crescimento da participação de fontes intermitentes, como a energia solar e eólica, na matriz elétrica tem acentuado a necessidade de sistemas de armazenamento capazes de atenuar as oscilações no suprimento e garantir a segurança energética. Dentre as tecnologias disponíveis, destacam-se as usinas hidrelétricas reversíveis (UHR); elas armazenam energia por meio do bombeamento de água para um reservatório elevado, permitindo sua posterior utilização para geração de energia elétrica. No entanto, limitações topográficas e ambientais podem restringir sua implementação. Nesse contexto, este estudo propôs um sistema alternativo de armazenamento baseado nos princípios das usinas hidrelétricas reversíveis, no qual o reservatório superior é substituído por um tanque pressurizado. Nessa configuração, a energia é armazenada por meio da compressão do ar confinado no interior do tanque. O estudo envolveu a modelagem matemática das etapas de bombeamento e turbinamento, seguida de simulação computacional utilizando a linguagem de programação Python. Os resultados permitiram analisar a evolução temporal das variáveis operacionais e avaliar a eficiência do sistema proposto, mostrando que o sistema, em sua configuração atual, apresentou menor eficiência do que as usinas hidrelétricas reversíveis convencionais. Assim, esta pesquisa apresenta o conceito do sistema e estabelece uma base para estudos futuros.

Palavras-chave: Armazenamento de Energia. Bombeamento. Turbina. Geração elétrica.

1. Introduction

In a scenario characterized by heavy reliance on fossil fuels, the demand for alternative energy sources has been growing, driven by the need to balance efficiency, reliability, and sustainability. However, the variability and intermittency of some of these sources—such as wind and solar power, given their dependence on weather and climatic conditions—pose a challenge to the management of energy systems, which must adapt to fluctuations in supply (Wang & Zou, 2024).

Thus, the transition to an energy system based primarily on renewable sources raises issues related to security of supply and quality of service. Although initiatives such as combining different types of complementary generation and implementing more advanced conversion and transmission technologies help mitigate the problem, these measures may be insufficient in the face of growing energy demand and the integration of variable renewable energy sources. In this context, grid-integrated energy storage systems stand out as promising solutions capable of enhancing the security and flexibility of the power system (HELM *et al.*, 2021).

These systems operate by converting electrical energy into another form of energy (e.g., potential, kinetic, or chemical energy) during periods when production exceeds demand, allowing the stored energy to be converted back into electrical energy when demand exceeds production, thereby reducing waste. Among the technologies designed for this purpose, pumped-storage hydropower (PSH) plants and compressed air energy storage (CAES) stand out due to their economic viability and large-scale storage capacity (Canales *et al.*, 2015; Zhang *et al.*, 2024).

Pumped-storage hydropower (PSH) plants store energy by pumping water into an elevated reservoir and later releasing it to drive hydraulic turbines. With a global installed capacity of 179

GW in 2023, PSH is the most widely used energy storage technology worldwide, mainly because of its technological maturity and favorable cost-effectiveness compared with other storage options, especially for long-duration applications (Canales *et al.*, 2015; IHA, 2024).

Advances in pumped-storage hydropower have been strongly associated with the development of variable-speed reversible units, which can operate at optimized rotational speeds while maintaining high efficiency under different head and load conditions. This flexibility is made possible by electrical machine and power-converter arrangements that allow rotational speed to vary without compromising grid compatibility. Converter-fed induction machines and doubly-fed induction machines have been identified as suitable alternatives for single-unit applications and modular configurations, respectively (Guo *et al.*, 2025; Jukić *et al.*, 2024; Jukić *et al.*, 2023).

Alternative PSH configurations have also been proposed to reduce limitations related to topography and water availability. One example is the closed-loop PSH system, in which water circulates between two reservoirs that are isolated from natural water courses. This arrangement allows installation in areas located far from rivers. Based on this concept, 616,000 potential sites have been identified worldwide, representing a combined energy storage potential of 23.1 million GWh (Stocks *et al.*, 2021).

In addition to these technological and siting-related developments, several studies have investigated hybrid systems based on pumped-storage hydropower principles. Hunt *et al.* (2014), for example, proposed integrating large-scale pumped-storage stations with cascading dams, enabling energy storage for electricity generation during drought periods and achieving storage efficiencies of up to 90%. Onu *et al.* (2022) analyzed the integration of photovoltaic generation with PSH systems, emphasizing small off-grid installations in rural areas and their contribution to community-based energy supply.

Given the need to increase power-system flexibility, energy storage systems are important not only for compensating for generation fluctuations but also for providing ancillary services. These services include load following, energy reserves, frequency regulation, and support for the economic operation of the power system (Daim *et al.*, 2012). In addition, the strategic placement of storage systems can affect power flows, reduce losses, and ease transmission-capacity constraints (EPE, 2021).

In Brazil, the deployment of energy storage technologies has been slower because hydroelectric plants still play a dominant role in the electricity mix. However, the reduction in new hydropower projects, mainly due to siting difficulties and socio-environmental impacts, together with the need to diversify renewable energy sources, makes energy storage an important option for meeting peak demand and providing ancillary services (EPE, 2021).

In the Brazilian interconnected power system, hourly and seasonal tariffs have been applied to high-voltage consumers since 1982. These tariffs vary according to demand periods and tariff flags, encouraging consumers to reduce grid use during peak hours, when electricity costs are higher. Although this measure helps flatten the load curve and reduces stress on generation, transmission, and distribution infrastructure, it does not eliminate the need for effective solutions such as energy storage (EPE, 2023).

Based on this context, this study examines a storage system inspired by PSH systems, in which the upper reservoir is replaced by a pressurized reservoir. In this configuration, surplus electricity is used to pump water into the reservoir, gradually compressing the confined air. As a result, the storage mechanism changes from gravitational potential energy to energy stored through air compression. During generation, the compressed air expands and drives the water through a

Pelton turbine, forming an alternative storage approach that combines principles of hydropower and compressed-air energy storage.

2. Description of the Proposed System and Operating Principle

Figure 1 shows the schematic diagram of the proposed storage system, based on the operating principles of pumped-storage hydropower (PSH) plants. The arrangement comprises the main components of the facility, including a lower reservoir open to the atmosphere and a sealed, pressurized reservoir. These components are interconnected through the pumping and turbine systems, which operate according to the energy storage and generation requirements.

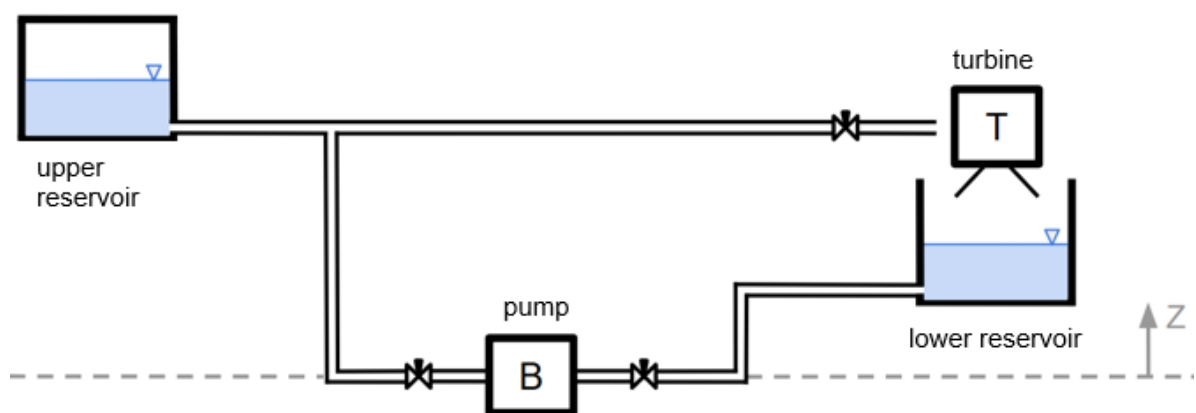


Figure 1 – Schematic representation of the proposed storage system.

The system's operation consists of a cyclical process of energy storage and generation. Thus, during periods of low electricity demand and lower electricity tariffs, water is transferred from the lower reservoir to the pressurized reservoir via the pumping system; this process compresses the air confined within the reservoir. In this way, energy is stored both as gravitational potential energy, associated with the elevation of the water, and through the compression of the air confined within the pressurized reservoir. Furthermore, given the wide operating pressure range and the high pressures reached at the end of the pumping stage, the system employs positive-displacement pumps, which are suitable for operation under such conditions.

During the generation stage, which corresponds to periods of peak electricity demand and higher electricity tariffs, the process is reversed, and the stored energy is converted back into electrical energy. To achieve this, the water in the pressurized reservoir is forced out by the expanding compressed air and flows toward the Pelton turbine, which was selected for this project because of its suitability for high-head conditions and its operational flexibility over a range of flow rates.

Unlike conventional pumped-storage hydropower (PSH) plants, such as the Hohenwarte II plant in Germany shown in Figure 2, the proposed design does not depend on an elevation difference between reservoirs to store energy. Instead, it uses a hybrid storage mechanism in which energy is stored by compressing the air inside the pressurized reservoir, rather than relying on gravitational head. This feature provides greater flexibility in the arrangement of the system components and may facilitate its implementation in areas with topographical limitations.



Figure 2 – Hohenwarte II hydroelectric plant (Vattenfall, 2026).

3. Method

This section describes the methodological procedure adopted for the development and analysis of the proposed storage system. Initially, a mathematical model was formulated to represent the operational stages and derive expressions for the operational variables over time. Next, computational simulations were performed in Python to implement the developed model and analyze the system's dynamic behavior under different operating conditions through graphical and quantitative analyses.

3.1. Proposed Mathematical Model

The system's model was divided into two stages: pumping and turbine operation. For each stage, the proposed configurations, adopted simplifications, and governing equations are presented to make the analysis mathematically tractable. These equations describe how the relevant variables change over time and enable the estimation of the energy consumed during pumping and generated during turbine operation.

3.1.1. Simplifications Adopted

The following assumptions regarding the system configuration were made to simplify the mathematical modeling: absolute pressure p_1 [Pa] was assumed to be equal to atmospheric pressure p_{atm} ; velocities v_1 and v_4 [m/s] were assumed to be negligible; and the head losses were also assumed to be negligible because of the short piping length and their small magnitude compared to absolute pressure p_4 (pressurized air). Furthermore, the reservoirs were assumed to be vertical, with constant cross-sectional areas A_1 and A_4 [m²]. For the pumping stage, the flow rate Q [m³/s] was assumed to remain constant throughout the process.

3.1.2. Pumping

Figure 3 illustrates the system configuration during the pumping stage, highlighting the elements involved in transferring water from the lower reservoir to the pressurized reservoir.

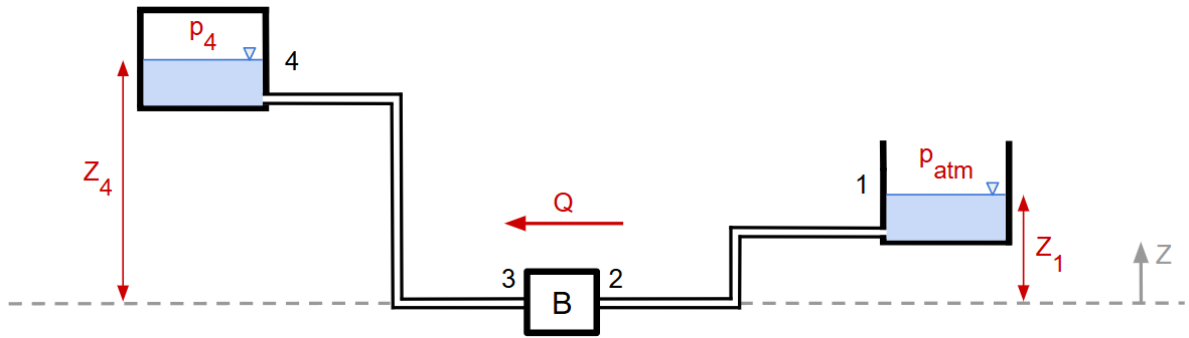


Figure 3 – Schematic representation of the system during pumping.

3.1.2.1. Application of the Energy Equation to Pumping

The analysis of the pumping stage began with the application of the energy equation to the endpoints of the pumping system—defined in Figure 3 as point 1 (water surface in the lower reservoir) and point 4 (water surface in the pressurized reservoir), presented by Equation 1.

$$H_u = \frac{p_4}{\rho g} + Z_4 + \frac{v_4^2}{2g} - \left(\frac{p_1}{\rho g} + Z_1 + \frac{v_1^2}{2g} \right) \quad (1)$$

where H_u denotes the total head [m], p the pressure [Pa], Z the elevation [m], v the velocity [m/s], g the gravitational acceleration [m/s²], and ρ the density of water [kg/m³].

Applying the simplifications adopted yields Equation 2, which provides the required pump head.

$$H_u = \frac{p_4}{\rho g} + Z_4 - \left(\frac{p_{atm}}{\rho g} + Z_1 \right) \quad (2)$$

3.1.2.2. Behavior of air

To describe the behavior of the air confined within the pressurized reservoir, the ideal gas law was adopted, as shown in Equation 3. For a fixed mass of air at constant temperature, this relationship indicates that the air pressure varies inversely with its volume.

$$p_4 Vol_{air} = m_{ar} RT \quad (3)$$

where Vol_{air} is the volume of air retained in the reservoir [m^3], m_{air} is the mass [kg], R is the universal gas constant [$J/kg \cdot K$], and T is the temperature [K].

The change in air volume over time, $Vol_{air}(t)$, results directly from the amount of water pumped into the reservoir. For the time t_p elapsed since the start of the pumping process, the Vol_{air} is described by Equation 4.

$$Vol_{air} = Vol_{air,max} - \int_0^{t_p} Q dt = Vol_{air,max} - Qt_p \quad (4)$$

where $Vol_{air,max}$ is the volume [m^3] at the start of pumping process, and t_p is the elapsed time [s] since the start of the pumping process.

Substituting Equation 4 into Equation 3 yields Equation 5, which defines pressure p_4 as a function of time t_p .

$$p_4 = \frac{m_{air} RT}{Vol_{air,max} - Qt_p} \quad (5)$$

3.1.2.3. Water level

The advance of the water surface over time t_p in the two reservoirs, $Z_1(t)$ and $Z_4(t)$, was determined using Equations 6 and 7.

$$Z_1 = Z_{1,max} - \frac{Q}{A_1} t_p \quad (6)$$

$$Z_4 = Z_{4,min} + \frac{Q}{A_4} t_p \quad (7)$$

where $Z_{1,max}$ and $Z_{4,min}$ [m], are the water levels in the suction and discharge reservoirs, respectively, measured at the start of pumping.

3.1.2.4. Total head

Considering Equations 5, 6, and 7, Equation 2 was rewritten as Equation 8, which describes the total head of the pumping system over time.

$$H_u = \frac{m_{air} RT}{(Vol_{air,max} - Qt_p)\rho g} + Z_{4,min} + \frac{Q}{A_4} t_p - \frac{p_{atm}}{\rho g} - Z_{1,max} + \frac{Q}{A_1} t_p \quad (8)$$

3.1.2.5. Required Power

The required shaft power is given by Equation 9.

$$Power_{pump} = \frac{\rho Q g H_u}{\eta_{pump}} \quad (9)$$

where η_{pump} is the efficiency during the pumping phase.

Substituting Equation 8 into Equation 9 yields Equation 10, which represents the instantaneous shaft power required by the pump over time.

$$Power_{pump} = \frac{\rho Q g}{\eta_{pump}} \left[\frac{m_{air} R T}{(Vol_{air,max} - Q t_p) \rho g} + Z_{4,min} + \frac{Q}{A_4} t_p - \frac{p_{atm}}{\rho g} - Z_{1,max} + \frac{Q}{A_1} t_p \right] \quad (10)$$

3.1.3. Turbine Operation

The turbine discharge process was modeled using an incremental method that represents the gradual change in the volume of air confined in the pressurized reservoir during discharge. This approach made it possible to track, at each iteration, the main variables related to flow behavior and system performance. In this formulation, $\alpha_{initial}$ [%] represents the initial percentage of the reservoir volume occupied by air, while $\Delta\alpha$ [%] denotes the increment in the air-volume fraction at each iteration. The index j was used to identify each calculation step.

Figure 4 illustrates the system configuration during the generation stage, highlighting the elements involved in the operation, with particular emphasis on the interaction between the water jet leaving the injector and the turbine runner, through which the kinetic energy of the water jet is converted into mechanical energy at the turbine shaft.

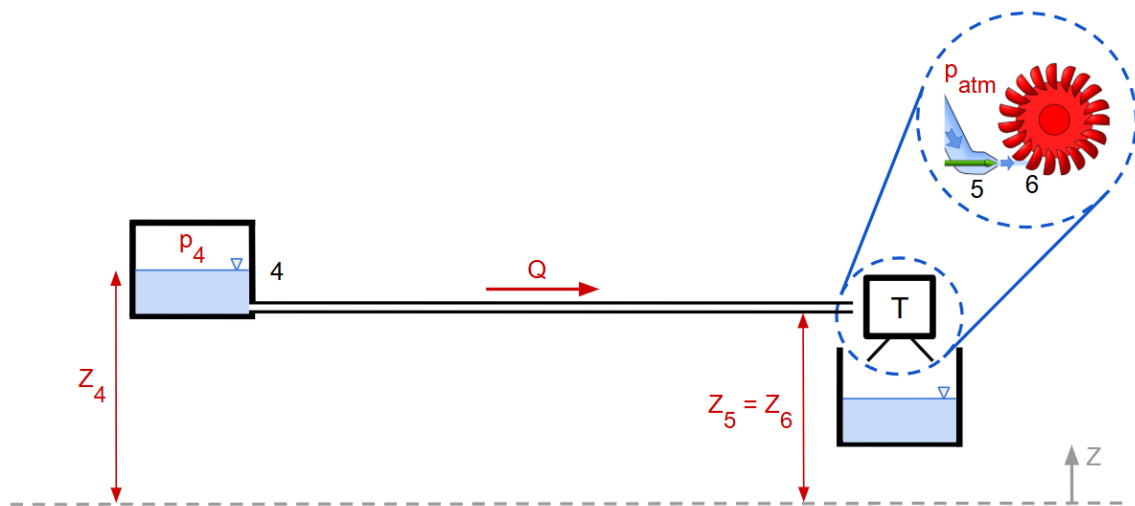


Figure 4 – Schematic representation of the system during the turbine stage, with a close-up of the injector/turbine.

3.1.3.1 Air Pressure in the Reservoir

During discharge, the expansion of the compressed air occurred slowly, which supports the hypothesis of an isothermal process. Based on this consideration, the variation in air pressure in the reservoir throughout the operation was calculated using Boyle's Law, as shown in Equation 11.

$$p_{4,j} = p_{4,\text{initial}} \left(\frac{\alpha_{\text{initial}}}{\alpha_{\text{initial}} + j \cdot \Delta\alpha} \right) \quad (11)$$

3.1.3.2 Jet velocity and flow rate

Applying Bernoulli's equation between points 4 (water surface in the pressurized tank) and 5 (injector outlet) during turbine operation yields Equation 12, which expresses the jet velocity at the injector outlet, $v_{5,j}$.

$$v_{5,j} = \sqrt{\frac{2 p_{4,j}}{\rho}} \quad (12)$$

From this velocity, the flow rate Q_j , was determined using Equation 13,

$$Q_j = v_{5,j} \cdot A_5 \quad (13)$$

where A_5 is the cross-sectional area of the jet.

3.1.3.3. Time of turbine operation

The time interval Δt_j corresponding to each iteration j was calculated based on the incremental change in the volume of water in the pressurized reservoir. Considering the average flow rate between two consecutive iterations, Equation 14 was applied to determine the corresponding time interval.

$$\Delta t_j = \frac{Vol_{\text{water},j-1} - Vol_{\text{water},j}}{\frac{Q_{j-1} + Q_j}{2}} \quad (14)$$

Thus, the time elapsed since the start of the discharge was determined cumulatively using Equation 15.

$$t_j = t_{j-1} + \Delta t_j \quad (15)$$

3.1.3.4. Head at the turbine

Assuming that the jet's kinetic energy was fully transferred to the turbine runner, the head H_j was defined by Equation 16, obtained by applying the energy equation between point 5 (injector outlet) and point 6 (Pelton bucket).

$$H_j = \frac{v_{5,j}^2}{2g} \quad (16)$$

3.1.3.5. Power Output

The mechanical power delivered at the turbine shaft at each iteration j was obtained using Equation 17.

$$Power_{\text{turb},j} = \rho g Q_j H_j \eta_{\text{turbine}} \quad (17)$$

Adopted $\eta_{\text{turbine}} = 0.9$

3.1.3.6. Energy Generated

The total mechanical energy delivered at the turbine shaft during turbine operation was obtained by integrating the shaft power over time. Considering the incremental process described, this integration was performed numerically by summing the energy contributions over the intervals Δt_j , as shown in Equation 18.

$$E = \sum_{j=1}^n Power_{\text{turb},j} \Delta t_j \quad (18)$$

3.2. Simulation

To apply and analyze the developed mathematical model, computational simulations were performed in Python to numerically simulate the pumping and turbine operation stages. The scripts implemented the equations derived in Section 3.1, allowing the dynamic behavior of the system over time to be evaluated by analyzing the operational variables. In addition, the simulations provided useful data for energy and efficiency analyses.

The simulations were structured in two parts: the first dedicated to the pumping stage, involving water transfer and air compression, and the second dedicated to the turbine stage, involving the discharge of pressurized water and energy conversion.

To enable computational implementation, the following Python libraries were used:

- NumPy, for vector data processing and numerical calculations over time;
- Pandas, for organizing and manipulating simulated variables using *DataFrames*;
- SciPy, for fitting polynomial curves for integration purposes;
- Matplotlib, for generating graphs representing the simulated variables.

3.2.1. *Pumping Simulation*

The pumping stage was simulated using Equations 3 to 10. The code first defined the system's physical, geometric, and operational parameters to represent its behavior over time. These parameters included the reservoir's volume, diameter and height, installation elevations, minimum and maximum air-volume fractions, pump efficiency, and flow rate. The air mass, temperature, water density, and gravitational acceleration were also specified.

The simulation was then conducted iteratively, with a predefined time step. At each time step, the code calculated the air volume in the reservoir, the internal pressure, the water levels in each reservoir, the total head of the system, and the power consumed by the pump. These values were stored in data structures and subsequently used to estimate energy consumption.

The energy consumed during pumping was obtained by integrating the fitted power curve. Additionally, the code calculated the percentage distribution of energy consumption over equal time intervals. The results were visualized using graphs, allowing the evolution of the main variables to be evaluated.

3.2.2. *Turbine Simulation*

The turbine simulation was developed using Equations 11 to 18. An incremental method was applied to represent the gradual water discharge and the expansion of the confined air through discrete variations in the air-volume fraction

Initially, the physical and geometric parameters of the system were defined, including the reservoir dimensions, air mass, initial and minimum pressures, initial air fraction, and the percentage increment applied at each iteration. Relevant physical constants, such as gravitational acceleration and water density, were also entered.

The simulation evaluated the system behavior during water discharge from the pressurized reservoir. At each iteration, the code updated the air fraction and the discharged water volume, then calculated the new internal pressure using Boyle's law under the assumption of isothermal expansion. From this pressure, the head, water-jet velocity, and instantaneous flow rate were determined. The incremental discharge time was estimated from the average between the current and previous flow rates. This procedure was repeated until the pressure reached the predefined minimum limit, marking the end of the operation.

Using the accumulated data, the mechanical power delivered at the turbine shaft, and the percentage distribution of shaft power over equal time intervals were calculated, enabling the turbine's performance to be evaluated. Finally, the results were presented using graphs.

4. Results

This section presents the results obtained from the computational simulations based on the mathematical model described previously, organized to highlight the temporal variations of the key operational variables. The implementation of the Python scripts allowed for the analysis of the dynamic behavior of the proposed system.

4.1. *Pumping Results*

The computational simulation of the pumping stage generated a dataset used to analyze the temporal evolution of the total head, hydraulic power, and the distribution of energy consumption throughout the process.

Three distinct reservoir configurations were analyzed, combining different volumes and diameters, as shown in Table 1. The diameters were calculated to maintain the same height. In all configurations, an elevation difference of 1 m was assumed between the lower reservoir and the pressurized reservoir.

In all configurations, an elevation difference of 1 m was assumed between the bottoms of the pressurized reservoir and the lower reservoir.

Table 1 – Dimensions of the reservoir pairs in each simulated configuration.

Configuration	Reservoir Volume / m ³	Height / m	Diameter / m
1	1,000	12.7	10
2	10,000	12.7	31.6
3	20,000	12.7	44.7

Air compression in the pressurized reservoir was modeled by reducing the air volume fraction from 80% to 10% of the total reservoir volume, starting from an initial gauge pressure of 5 barg, corresponding to an initial absolute pressure of 6.013 bar. The total simulated pumping time was 3 hours, divided into 100 uniform time increments. In addition, the pump efficiency was assumed to be constant at 65%.

The total head-versus-time curves (Figure 5) were identical for the three cases studied, showing a marked increase in head throughout the operation. As the air volume decreased due to compression, the internal absolute pressure of the reservoir increased nonlinearly, thereby increasing the total head. This behavior reflected the strong dependence of the required pump head on pressure variations inside the reservoir.

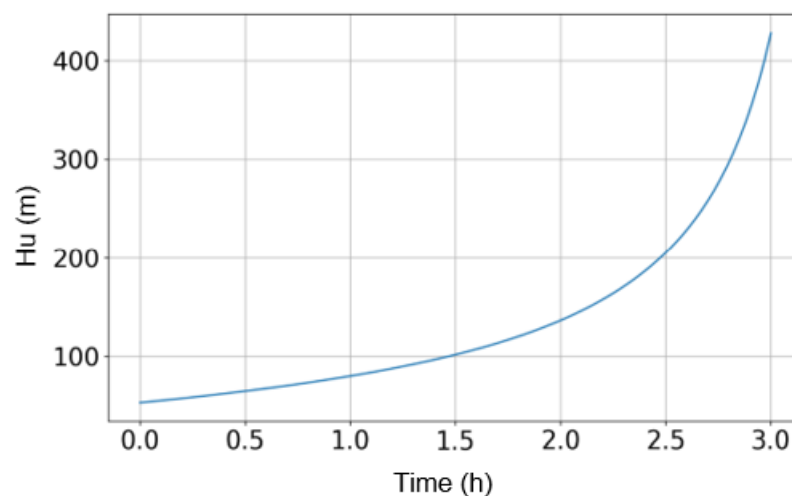


Figure 5 – Temporal variation of the pumping head for the simulated cases.

The pump-power curves in Figure 6 followed the same pattern as the head curves over time. As the internal pressure in the pressurized reservoir increased, the power required for pumping rose substantially, especially near the end of the process. Higher reservoir volumes also resulted in greater pump-power demand.

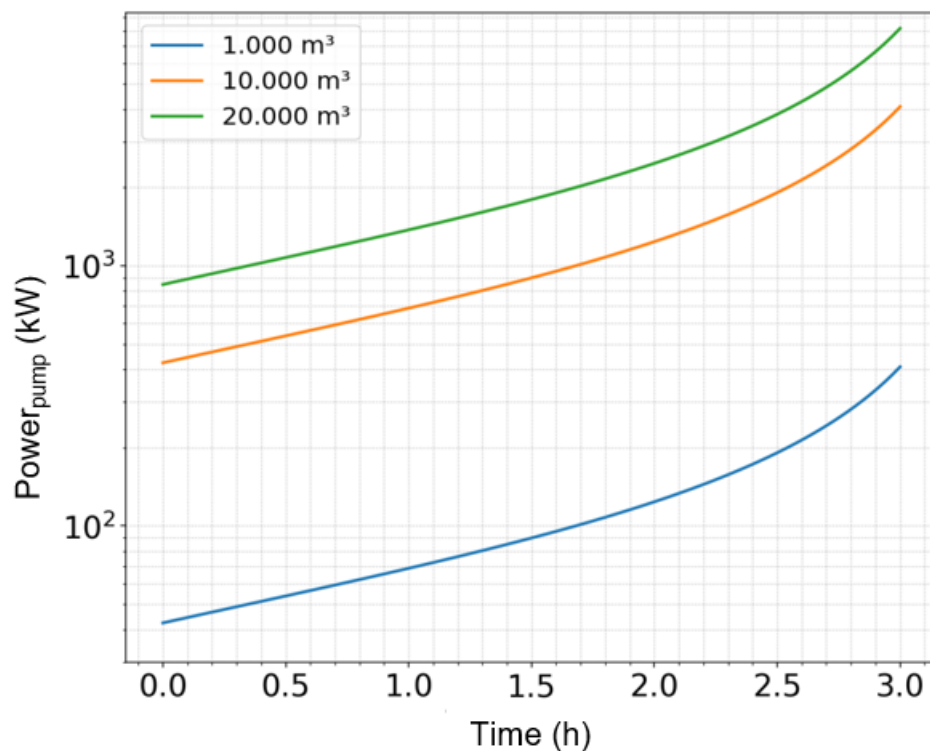


Figure 6 – Temporal variation of the power required for pumping in the simulated cases, presented on a single-logarithmic scale.

The total energy consumed during the pumping operation, obtained by numerically integrating the power data over time, is shown in Table 2.

Table 2 – Energy consumed during pumping according to the simulated configuration.

Configuration	Reservoir Volume / m³	Energy Consumed / kWh
1	1,000	359
2	10,000	3,592
3	20,000	7,183

Figure 7 shows the fraction of total energy consumed in each 10% interval of the time pumping operation.

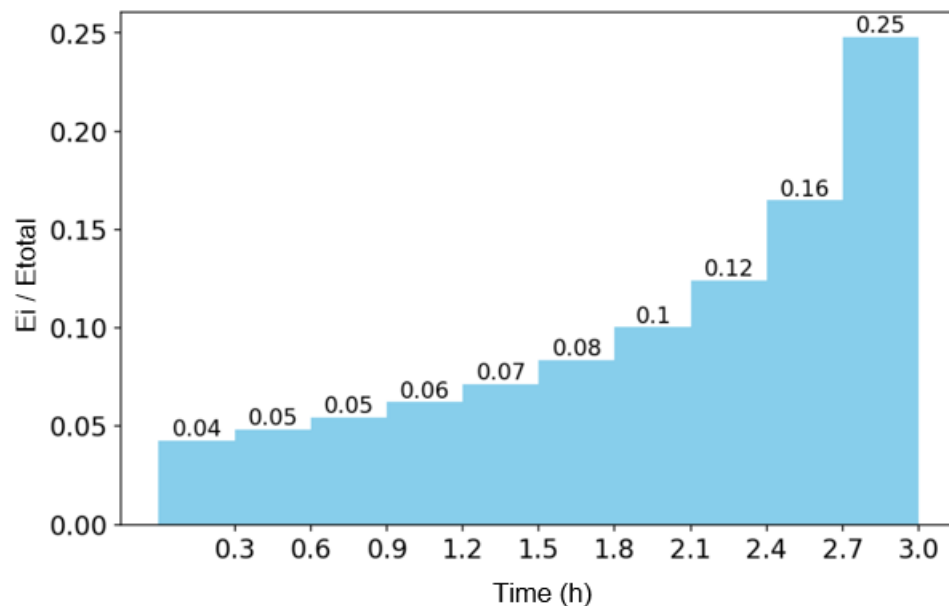


Figure 7 – Fraction of total energy for each tenth of the pumping time.

The three simulations showed similar trends, indicating that system operation was mainly governed by the rise in internal pressure and the resulting increase in pump power demand. Energy consumption became increasingly concentrated near the end of the process, with the largest fraction occurring during the final 30% of the total operating time. This result reveals a consistent operating pattern, defined by a clear pump-power profile strongly affected by air compression inside the pressurized reservoir

4.1. Turbine Operation Results

The turbine-stage simulation used the same pressurized reservoirs considered in the pumping analysis. During operation, the pressurized air expanded from an initial gauge pressure of 40 barg to a final gauge pressure of 5 barg, corresponding to absolute pressures of approximately 41.013 bar and 6.013 bar, respectively. As the air expanded and water was discharged, the air-volume fraction increased from an initial value of 10%, with increments of 0.001 percentage points per iteration. Each simulation was set to last 3 h, with an allowable tolerance of 6 min, equivalent to 10% of 1 h.

The head-versus-time curves in Figure 8 exhibit a continuous decrease throughout the operation, reflecting the progressive depressurization of the pressurized reservoir. The curves exhibit smooth and consistent behavior, resulting from the gradual discharge of water and expansion of the confined air. This reduction in pressure decreases the available head and consequently influences the jet velocity, flow rate, and turbine power.

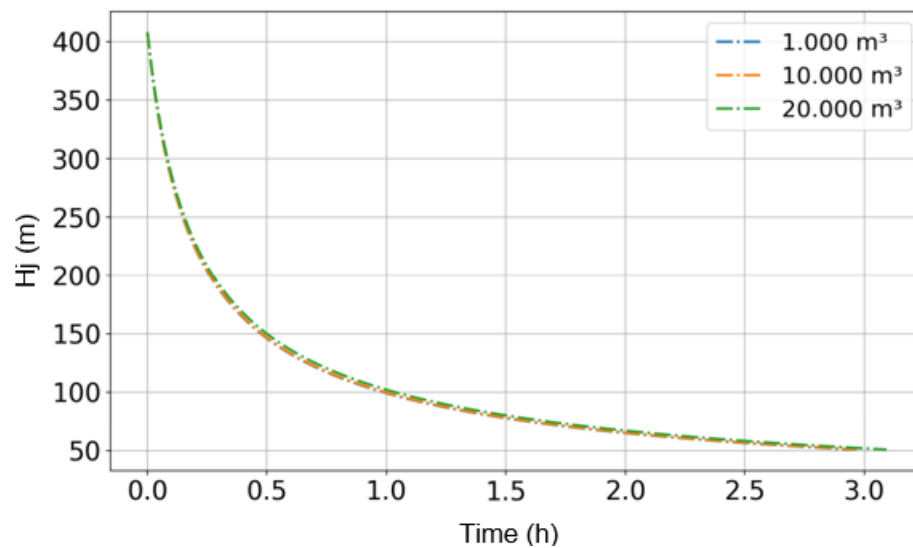


Figure 8 – Temporal variation of head during turbine operation for the simulated cases.

Figure 9 shows the variation in flow rate over time, highlighting the relationship between flow-rate magnitude and pressurized-reservoir volume at equivalent stages of operation.

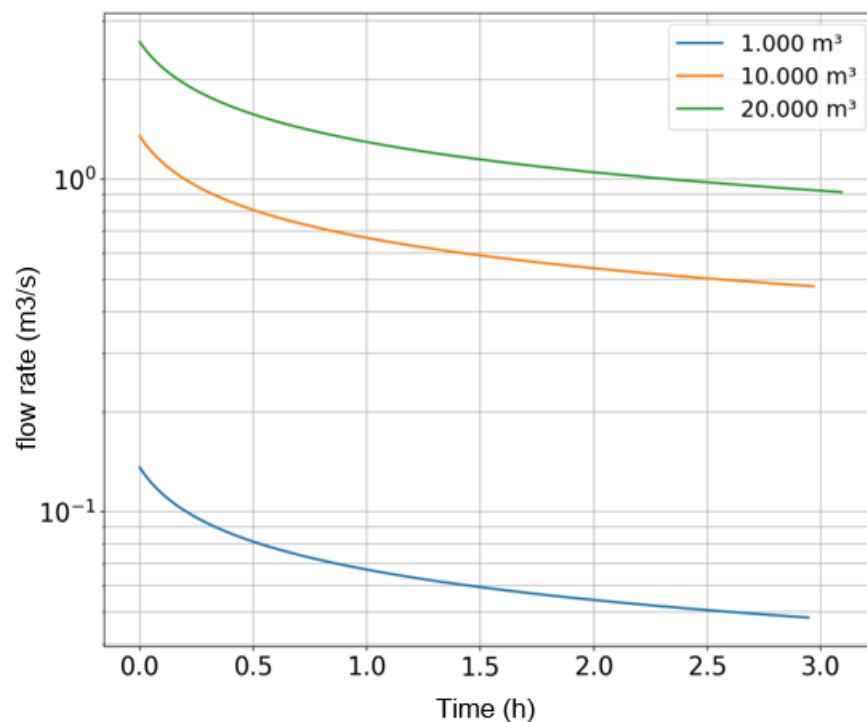


Figure 9 – Temporal variation of the flow rate in the turbine for the three simulated cases, presented on a single-logarithmic scale.

Figure 10 presents the turbine shaft power as a function of time. The substantial drop in turbine shaft power during the first hour of operation highlights the effect of reservoir depressurization on the mechanical power at the turbine shaft.

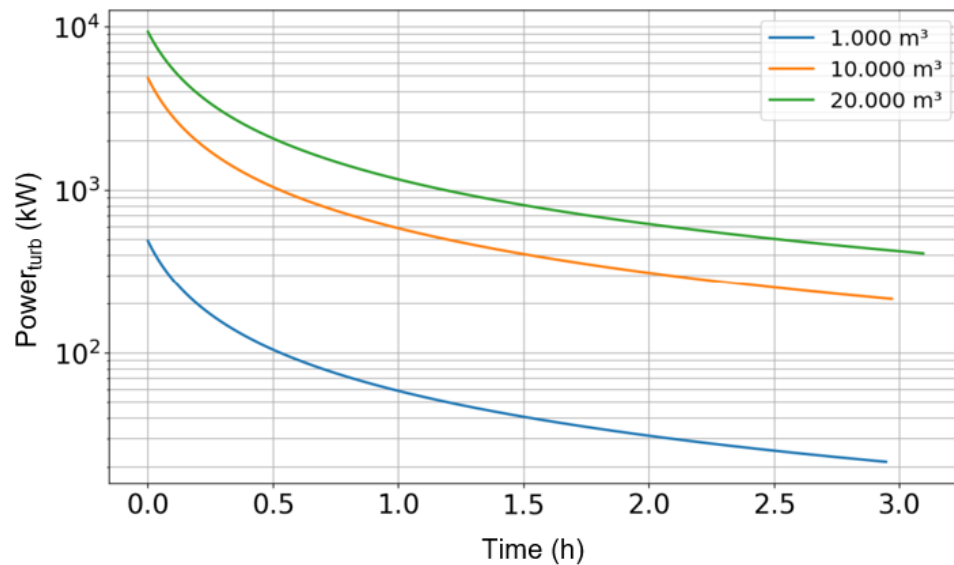


Figure 10 – Temporal variation of the power generated by the turbine for the simulated cases.

The total energy generated in turbine operation for each reservoir is shown in Table 3.

Table 3 – Energy generated during turbine operation according to the simulated configuration.

1	1,000	208
2	10,000	2,078
3	20,000	4,156

The graph in Figure 11 shows the fraction of the total energy generated during each 10% interval of the turbine operating time for the configuration with 1,000 m³ reservoir. Similar behavior was observed for the other two reservoir configurations, with a larger fraction of the total energy being delivered during the initial stages of operation. More than half of the total energy was delivered during the first 20% of the operation.

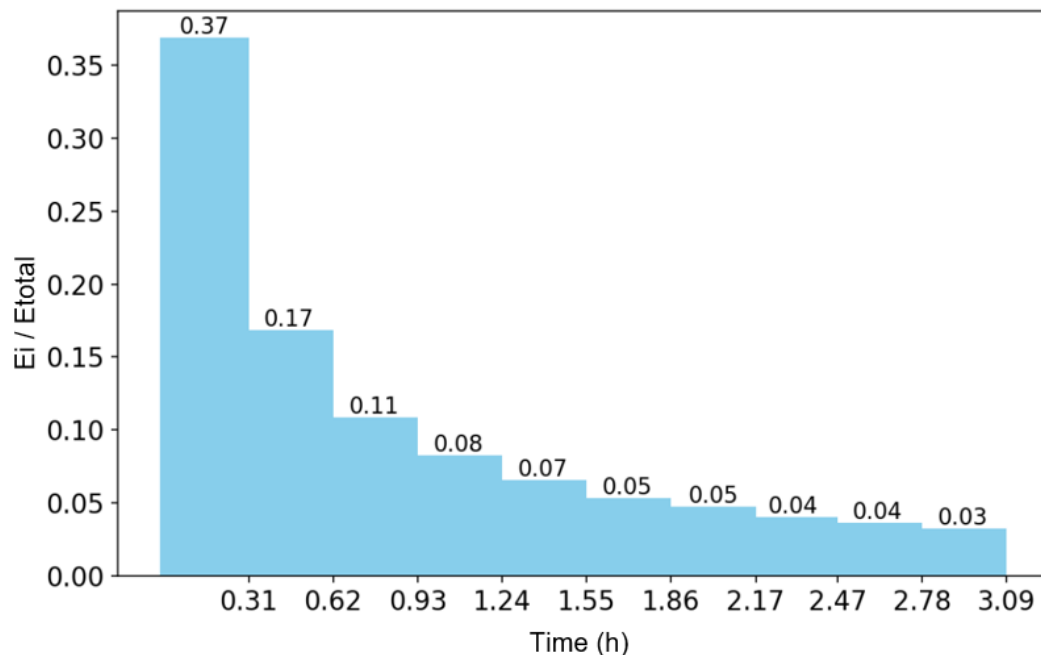


Figure 11 – Proportion of total energy in each tenth of the turbine operation time for the simulated cases.

5. Discussion of Results

Analysis of the results provided a more comprehensive understanding of the system's operational dynamics and supported the technical evaluation of the proposed pressurized hydraulic energy storage system. The behavior of the simulated curves highlighted the interaction between the thermodynamic and hydraulic phenomena involved.

The power curve during pumping showed a pronounced increase in the final stages of the process, reflecting the nonlinear nature of air compression. As the gas volume decreased, the internal pressure increased nonlinearly, increasing the required pump head and, consequently, the pump power. This behavior suggests that, in a practical application, the pumping system would require positive displacement pumps.

During turbine operation, the opposite trend was observed: the turbine shaft power reached its maximum values at the beginning of the operation, when the internal pressure of the pressurized reservoir was still high, and then gradually decreased as the air expanded. This characteristic resulted in a high initial power output followed by a progressive decline, suggesting possible applicability to short-duration energy-storage services. On the other hand, this behavior may limit the system's suitability for longer-duration energy delivery compared with conventional pumped-storage hydropower plants.

The system's round-trip efficiency was defined as the ratio of the total energy delivered during turbine operation to the total energy consumed during pumping. For the three simulations, this value was 58%. The round-trip efficiency is associated with the efficiencies assumed for the pump and turbine.

The results showed that the pressurized hydraulic storage system with a compressed-air reservoir exhibited consistent simulated dynamic behavior and high initial power output. However, in terms of energy efficiency, the configuration studied was inferior to conventional pumped-storage hydropower plants (PSHPs), which exhibit round-trip efficiencies ranging from 70% to 85%, according to the European Association for Storage of Energy (EASE) (2016). Nevertheless, the results suggest potential for short-duration energy-storage applications.

6. Conclusions

This study evaluated, through mathematical modeling and computational simulation, the feasibility of a hybrid energy storage system based on a pressurized reservoir. The quantitative results including the round-trip efficiency and the power and energy curves showed that the current configuration exhibits limited energy efficiency when compared with conventional pumped-storage hydropower systems.

Nevertheless, the proposed system may provide advantages in deployment and geographic flexibility. Because it does not require large elevation differences, it could be installed in areas where conventional pumped-storage hydropower plants are limited by topographical constraints. This feature may broaden its potential for grid integration as a modular alternative with lower environmental impact. The high initial power output observed over short-time intervals, combined with the non-dependence on large elevation differences, suggests potential for specific short-duration applications.

In summary, this study proposed the physical and operational concept of the system and establishment elements for future studies. Further work could focus on improving energy efficiency through more detailed thermodynamic and fluid-dynamic models, as well as integrating solar photovoltaic or wind generation to support the pumping process. This work pretends to contribute to the field of energy storage by presenting an numerically evaluating an alternative storage concept.

Acknowledgment

The authors would like to acknowledge the CNPQ.

References

- Canales, F. A., Beluco, A., & Mendes, C. A. B. (2015). Pumped storage hydropower in Brazil and the world: Application and perspectives. *Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental*, 19(2), 1230–1249. <https://doi.org/10.5902/2236117016002>
- Daim, T. U., Li, X., Kim, J., & Simms, S. (2012). Evaluation of energy storage technologies for integration with renewable electricity: Quantifying expert opinions. *Environmental Innovation and Societal Transitions*, 3, 29–49. <https://doi.org/10.1016/j.eist.2012.04.003>
- Empresa de Pesquisa Energética. (2021). *Usinas hidrelétricas reversíveis (UHR): Desafios para inserção em mercados de energia elétrica* [Pumped-storage hydropower plants: Challenges for integration into electricity markets]. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-561/EPE-DEE-NT-013_2021-r0.pdf
- Empresa de Pesquisa Energética. (2023). *Geração distribuída a diesel no horário de tarifa de ponta* [Diesel-fueled distributed generation during peak tariff hours]. <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-732/Gera%C3%A7%C3%A3o%20Distribu%C3%ADa%20a%20Diesel%20no%20Hor%C3%A1rio%20de%20Tarifa%20de%20Ponta.pdf>
- European Association for Storage of Energy. (2016). *Energy storage technology descriptions: Pumped hydro storage*. https://energystorageeurope.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_PHS.pdf
- Guo, L., Xu, C., Zhang, F., Deng, F., Ai, X., & Xue, F. (2025). Variable speed pumped storage units in China: Current status and development. *Energy Reports*, 13, 2815–2828. <https://doi.org/10.1016/j.egyr.2025.02.017>
- Hunt, J. D., Freitas, M. A. V., & Pereira Junior, A. O. (2014). Enhanced pumped storage: Combining pumped storage in a yearly storage cycle with cascaded dams in Brazil. *Energy*, 78, 513–523. <https://doi.org/10.1016/j.energy.2014.10.038>

- Jukić, D.-K., Kugi, A., & Kemmetmüller, W. (2023). Optimal dynamic operation of pumped storage power plants with variable and fixed-speed generators. *Control Engineering Practice*, 138, 105601. <https://doi.org/10.1016/j.conengprac.2023.105601>
- Jukić, D.-K., Kugi, A., & Kemmetmüller, W. (2024). Optimal operation of pumped storage power plants with fixed- and variable-speed generators in multiple electricity markets considering overload operation. *Journal of Energy Storage*, 88, 111601. <https://doi.org/10.1016/j.est.2024.111601>
- Onu, U. G., Silva, G. S., de Souza, A. C. Z., Bonato, B. D., & da Costa, V. B. F. (2022). Integrated design of a photovoltaic power generation plant with a pumped hydro storage system and irrigation facility at the Uhuelele-Amoncha African community. *Renewable Energy*, 198, 1021–1031. <https://doi.org/10.1016/j.renene.2022.08.059>
- Stocks, M., Stocks, R., Lu, B., Cheng, C., & Blakers, A. (2021). Global atlas of closed-loop pumped hydro energy storage. *Joule*, 5(1), 270–284. <https://doi.org/10.1016/j.joule.2020.11.015>
- Vattenfall. (2026, March 24). *How algorithms are boosting pumped storage hydropower*. Vattenfall Group. <https://group.vattenfall.com/press-and-media/newsroom/2026/how-algorithms-are-boosting-pumped-storage-hydropower/>
- Wang, Y., & Zou, X. (2025). Stochastic operation strategy for emerging industry development and information transmission in financial markets: Evidence from intermittent China renewable energy resources. *Energy Reports*, 13, 1014–1028. <https://doi.org/10.1016/j.egyr.2024.12.058>
- Zhang, X., Gao, Z., Zhou, B., Guo, H., Xu, Y., Ding, Y., & Chen, H. (2024). Advanced compressed air energy storage systems: Fundamentals and applications. *Engineering*, 34, 246–269. <https://doi.org/10.1016/j.eng.2023.12.008>

Declarations

Authors' contributions

All authors reviewed and approved the final version of the manuscript and agree to be accountable for their respective contributions and for addressing any questions concerning the accuracy or integrity of the work. All authors have reviewed and confirmed the CRediT role assignments.

Funding information

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of interests

All authors have reviewed and approved this statement.

Data availability

All data supporting the findings of this study are included in the manuscript. No external datasets were used, and no additional data have been deposited in a public repository.

Declaration of artificial intelligence use

The authors declare that no generative artificial intelligence tools were used in the preparation of this manuscript.

Handling editor

Editor handled this article: **Ibrahim Ademola Fetuga.**