

Dual-Fluid Compressed Air Energy Storage for Renewable Integration: Thermodynamic Modeling and Performance Evaluation

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ABSTRACT

The increasing use of renewable energy sources such as wind and solar introduces fluctuations that make it more difficult to maintain a continuous balance between electricity generation and consumption. Energy storage systems play a critical role in addressing this challenge by storing excess energy and supplying it when needed. In this study, a hybrid storage approach known as Dual-Fluid Energy Storage (DFES) is investigated. The system combines compressed air with a water-based hydraulic mechanism, where energy is recovered through a Pelton turbine. A thermodynamic model based on polytropic behavior was developed and simulated using MATLAB/Simulink to analyze system performance under various operating conditions. The results show that a storage tank with a volume of 10 m³ at a pressure of 10 atm can provide an output of 100 kW for about 30 minutes, or maintain 10 kW for nearly 7 hours. When system losses are considered, the overall efficiency is calculated to be approximately 64%. The analysis also reveals that an initial water fill level of around 52% yields the highest usable energy, and this value remains largely unaffected by changes in pressure. In comparison with conventional hydraulic accumulators of similar size, the proposed system offers a significantly higher energy storage capacity per unit volume. These findings highlight the potential of hybrid compressed air systems and suggest the need for further experimental investigation and economic evaluation to assess their practical applicability in renewable energy systems.

تخزين طاقة الهواء المضغوط ثنائي السوائل لدمج مصادر الطاقة المتجددة: النمذجة الديناميكية الحرارية وتقييم الأداء

سالم عصمان بيت المال^{1,*}

الكلمات المفتاحية	الملخص
تخزين طاقة الهواء المضغوط نظام ثنائي السوائل محاكاة ديناميكية كفاءة الدورة الكاملة تكاملاً الطاقة المتجددة توربين بيلتون	يؤدي تزايد استخدام مصادر الطاقة المتجددة، كالطاقة الشمسية وطاقة الرياح، إلى تقلبات تُصعب الحفاظ على توازن مستمر بين توليد الكهرباء واستهلاكها. وتلعب أنظمة تخزين الطاقة دورًا حاسمًا في مواجهة هذا التحدي من خلال تخزين الطاقة الفائضة وتوفيرها عند الحاجة. في هذه الدراسة، تم بحث نهج تخزين هجين يُعرف باسم تخزين الطاقة ثنائي السوائل (DFES). يجمع هذا النظام بين الهواء المضغوط وآلية هيدروليكية مائية، حيث تُستعاد الطاقة من خلال توربين بيلتون. تم تطوير نموذج ديناميكي حراري قائم على السلوك متعدد الخواص، وتمت محاكاته باستخدام برنامج MATLAB/SIMULINK لتحليل أداء النظام في ظل ظروف تشغيل مختلفة. تُظهر النتائج أن خزان تخزين بحجم 10 أمتار مكعبة عند ضغط 10 ضغط جوي يُمكنه توفير طاقة 100 كيلوواط لمدة 30 دقيقة تقريبًا، أو الحفاظ على 10 كيلوواط لمدة 7 ساعات تقريبًا. وعند احتساب فاقد النظام، تُقدّر الكفاءة الإجمالية بنحو 64%. يكشف التحليل أيضًا أن مستوى تعبئة الماء الأولي الذي يبلغ حوالي 52% يُحقق أعلى طاقة قابلة للاستخدام، وتبقى هذه القيمة ثابتة إلى حد كبير بغض النظر عن تغيرات الضغط. وبالمقارنة مع خزانات الضغط الهيدروليكية التقليدية ذات الحجم المماثل، يوفر النظام المقترح سعة تخزين طاقة أعلى بكثير لكل وحدة حجم. تُبرز هذه النتائج إمكانات أنظمة الهواء المضغوط الهجينة، وتُشير إلى ضرورة إجراء المزيد من الدراسات التجريبية والتقييمات الاقتصادية لتقييم جدواها العملية في أنظمة الطاقة المتجددة.

Introduction

Driven by concerns about climate change and global warming, the global installed capacity of renewable energy grew by 50% in 2025. In the end of 2025, the global installed capacities of renewables such as solar, wind, hydropower, geothermal, marine, biogas, etc reached about 4,448.1 GW, from them 2,200 GW for PV solar energy systems, 1,021

GW for wind energy, about 96.8 GW electricity from biomass energy, the geothermal energy reached 16,873 MWe, and hydropower capacity stood at nearly 1,450 GW [1,2]. Prior to early 2024, the global cumulative installed capacity of compressed air energy storage (CAES) systems was approximately 1500 MWh. As of early 2026, the market is experiencing significant growth, with major projects in

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China leading the way in capacity, including the 300 MW/2,400 MWh Yingcheng station and a new 600 MW/2,400 MWh facility in Jiangsu [3].

Electricity systems worldwide are evolving as renewable energy sources take on a larger share of power generation. Wind and solar technologies provide clear environmental benefits, but their output is inherently variable because it depends on weather patterns and daily cycles. This fluctuation makes it more difficult to consistently match electricity supply with demand, especially in grids that rely less on traditional, controllable power plants. To manage these challenges, flexible solutions are required that can store surplus energy and release it when production is low. In this context, energy storage has become a key component in supporting reliable and efficient integration of renewable resources [4-32].

In recent years, a wide range of energy storage technologies has been developed, including mechanical, thermal, and electrochemical systems. Pumped hydro storage continues to be the most widely used option for large-scale applications due to its proven reliability and long service life. However, its expansion is limited by site-specific requirements such as terrain and water availability [33,34].

Compressed air energy storage has also been deployed at a commercial scale, but traditional systems often rely on fuel combustion during the expansion phase, which leads to emissions and reduces overall environmental benefits [35]. To address this issue, adiabatic designs have been introduced with the goal of capturing and reusing heat generated during compression. Although this approach can improve efficiency, it adds complexity and depends on effective thermal storage solutions, which remain a technical challenge [36,37].

At the same time, lithium-ion batteries have become widely used for short-duration storage because of their high efficiency and fast response times. Despite these advantages, concerns persist regarding raw material availability, performance degradation over time, and recycling at the end of their lifecycle [38,39]. Hybrid storage systems that combine different physical principles have received less attention. In particular, configurations that integrate compressed air with hydraulic mechanisms are not extensively studied. Most existing research has focused on gravity-based storage or conventional accumulator systems, indicating a need for further investigation into alternative hybrid designs [40,41].

In [42], a hybrid photovoltaic (PV)/wind/battery system was designed and evaluated under real climatic conditions for a residential application in southern Libya. The study demonstrated that the integration of solar and wind resources enhances system reliability due to their complementary characteristics, while battery storage ensures supply continuity. The results confirmed that the proposed system is capable of meeting the full load demand with favorable techno-economic performance, highlighting its suitability for off-grid rural electrification.

Although hybrid energy storage concepts are gaining interest, there is still a lack of studies that compare different system designs under the same operating conditions. Dual-fluid systems, in particular, have not been thoroughly evaluated alongside established technologies such as bladder accumulators and gravity-based storage using a consistent modeling approach.

This study addresses this gap by developing and analyzing a dual-fluid energy storage system within a unified framework. The main contributions of this work include the development

of a thermodynamic model that accounts for key loss mechanisms, simulation of system behavior to examine power and discharge characteristics, identification of optimal operating conditions such as fluid distribution, and a comparative assessment of different storage configurations under identical constraints. In addition, the study provides a clear and consistent method for evaluating round-trip efficiency based on component-level performance.

Methodology

Assumptions, limitations and uncertainties

To facilitate the analysis process, the following hypotheses were adopted without significantly affecting the validity of the results:

1. The process is reversible and adiabatic
2. The fluid is incompressible and treated as an ideal gas
3. The energy losses in the nozzle is neglected
4. Steady state, steady flow process
5. Constant efficiencies

The limitations of the research can be summarized as follows: the failure to provide an economic and environmental feasibility study for the proposed system, as well as the failure to specify the type of energy and the mechanism that will compress the air and water into the tank. Also, the present work is based solely on simulation results and has not been validated through experimental testing. These include treating the polytropic index as constant, neglecting frictional and minor losses within the system, and representing turbine performance using a simplified approach. Addressing these aspects in future work would improve the reliability of the results and provide a more realistic assessment of system behavior.

The source of uncertainty in the results lies in using thermodynamic equations under ideal conditions of insulation and reflectivity, and considering water and air as gases.

System Description (DFES)

The Dual-Fluid Energy Storage system is based on a closed vessel designed to contain both a compressible and an incompressible fluid. In this configuration (Fig. 1), water occupies a portion of the tank and acts as the hydraulic medium, while the remaining space is filled with compressed air. The stored energy is released when the compressed air exerts pressure on the water, forcing it out of the tank through a control valve and nozzle.

As the water is discharged, it forms a high-velocity jet that drives a Pelton turbine coupled to an electrical generator, thereby converting hydraulic energy into electricity. During this process, the air volume expands and its pressure decreases following a polytropic relationship, allowing energy extraction to continue until the internal pressure approaches atmospheric conditions. At that stage, a portion of the water can no longer be expelled, resulting in a residual volume that represents an unavoidable loss in the system.

The storage tank initially contains both water (approximately 52% of the total volume) and compressed air, with the expansion process characterized by a polytropic index of $n=1.3$. During operation, water is discharged through a valve to drive a Pelton turbine connected to a generator, producing electrical output power (P_{out}) measured in kilowatts.

Configurations for Comparison

To evaluate the performance of the proposed system, three different energy storage configurations were analyzed under identical conditions, specifically a storage volume of 10 m³ and an operating pressure of 10 atm. This approach ensures a consistent basis for comparison across all systems.

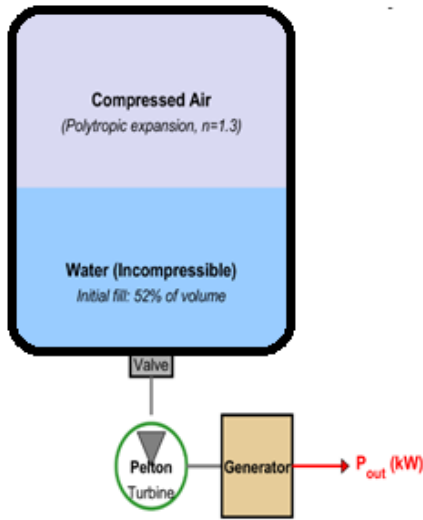


Figure 1: Schematic representation of the dual-fluid energy storage system

Table 1 presents an overview of the selected configurations, including their operating concepts as well as their primary strengths and limitations.

Table 1: Configurations, operating concepts and key strengths and limitations

Configuration	Operating Principle	Key Advantage	Key Limitation
DFES (proposed system)	Compressed air displaces water to drive a turbine	High energy density without combustion	Energy loss due to venting
Bladder accumulator	Flexible membrane separates gas and hydraulic fluid	Rapid response and clean operation	Reduced usable volume due to bladder
Gravity-based storage	Mechanical lifting of a mass using motor-generator systems	Simple design with long service life	Very low energy density per unit volume

The systems were chosen to represent different types of mechanical energy storage that do not rely on combustion processes [43]. Each configuration operates on a distinct physical principle and involves unique design trade-offs, making them suitable for a comparative assessment under the same boundary conditions.

Thermodynamic Modeling

The compression and expansion behavior of air within the system is described using a polytropic process. The work required for compression can be expressed as:

$$W_c = \frac{n}{n-1} mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \cdot \frac{1}{\eta_{mech} \cdot \eta_{thermal}} \quad (1)$$

In this expression, ($n = 1.3$) represents the polytropic index, which is commonly used to approximate moderately fast compression processes in compressed air systems. The term (m) denotes the mass of air, determined from the ideal gas relationship, while (R) and (T_1) correspond to the specific gas constant and initial temperature, respectively. Mechanical and thermal losses during compression are accounted for using efficiency factors of ($\eta_{mech} = 0.85$) and ($\eta_{thermal} =$

0.90), based on typical values reported in the literature [44]. The electrical power generated during discharge is derived from the hydraulic energy delivered to a Pelton turbine. This output can be written as:

$$P_{out} = \eta_{pelton} \cdot C_d \cdot \frac{\pi d_n^2}{4} \cdot \sqrt{2g\Delta h} \cdot \rho g \Delta h \quad (2)$$

Here, ($C_d = 0.62$) is the nozzle discharge coefficient, and ($\eta_{pelton} = 0.88$) represents the turbine efficiency [44]. The parameter (d_n) is the nozzle diameter, which is selected based on the desired operating power. The variables (ρ), (g), and (Δh) correspond to water density, gravitational acceleration, and effective hydraulic head, respectively.

Overall, the power output depends on the flow characteristics at the nozzle, the available hydraulic head, and the efficiency of the turbine-generator system. Losses occurring during compression, expansion, and energy conversion are incorporated into the model through the use of these efficiency terms, allowing for a more realistic representation of system performance.

Efficiency Formulation

The overall performance of the system was evaluated by combining the efficiencies of its main components into a single round-trip efficiency metric. This was calculated by multiplying the efficiencies associated with compression, thermal effects, turbine operation, and electricity generation:

$$\eta_{RT} = \eta_{mech,comp} \times \eta_{thermal,comp} \times \eta_{pelton} \times \eta_{gen} \quad (3)$$

Substituting the selected parameter values:

$$\eta_{RT} = 0.85 \times 0.90 \times 0.88 \times 0.95 = 0.639 \approx 64\% \quad (4)$$

The resulting efficiency is lower than earlier estimates but aligns more closely with reported values for compressed air systems that operate without combustion, which typically fall within the range of 50% to 65%. Calculating efficiency in this stepwise manner provides a more realistic estimate, as it explicitly accounts for losses at each stage of the energy conversion process and reduces the likelihood of overestimating system performance. Table 2 summarizes the efficiency assumptions used in the analysis, along with their sources and classification.

Table 2: Efficiencies of the devices

Parameter	Value	Source	Type
Compressor Mechanical efficiency	0.85	Typical industry assumption	Calibrated
Compressor thermal efficiency	0.90	Reported in CAES studies [44]	Literature
Pelton turbine efficiency	0.88	Reference [45]	Literature
Generator efficiency	0.95	Standard assumption	Calibrated

Simulation Framework

A time-dependent simulation model was developed in MATLAB/Simulink to analyze how key system variables such as pressure, flow rate, and power output evolve during operation. The model captures the dynamic interaction between the compressed air and the hydraulic discharge process.

To simplify the analysis, several assumptions were introduced. The air was treated as an ideal gas undergoing polytropic expansion, while the density of water was considered constant. Losses due to pipe friction and minor flow disturbances were not included at this stage and are intended to be incorporated in future refinements. In addition, the turbine was assumed to operate at a fixed efficiency corresponding to its design point.

A parametric study was carried out to evaluate system performance under different initial conditions. The fraction of the tank initially filled with water was varied between 10% and 90%, and simulations were performed at operating pressures of 5, 10, and 15 atm. This approach allowed the identification of trends and optimal operating ranges. The followed approach was illustrated in Fig. 2

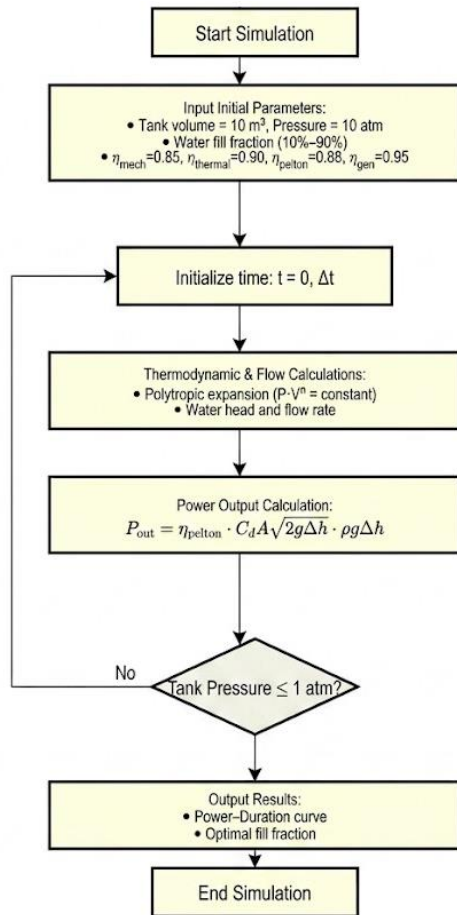


Figure 2: Flow diagram of the simulation procedure implemented in MATLAB/Simulink.

The model advances in discrete time steps, updating thermodynamic and flow variables at each iteration. At every step, the internal tank pressure is checked against atmospheric pressure. If the pressure remains above 1 atm, the calculation loop continues; otherwise, the simulation terminates and key performance indicators such as discharge duration, optimal fill fraction, and overall efficiency are recorded.

Results

Energy Storage and Efficiency

For the reference case of a 10 m³ storage tank operating at a pressure of 10 atm, the total energy stored in the system was estimated to be 23.4 kWh. When losses associated with compression, expansion, and energy conversion are taken into account, the usable electrical energy decreases to approximately 15.0 kWh. This corresponds to an overall round-trip efficiency of about 64%, reflecting the combined impact of all system components.

Power–Duration Relationship

The simulation results reveal a clear trade-off between output power and discharge time. Higher power levels can be sustained only for shorter periods, while lower power output allows for extended operation. For example, the system is

capable of delivering 100 kW for roughly 30 minutes, whereas reducing the output to 10 kW extends the operating time to approximately 6.75 hours, as it illustrated in Fog. 3. This trend is consistent with the fixed energy capacity of the system, where increasing power demand accelerates energy depletion. In addition, higher flow rates at elevated power levels lead to increased hydraulic losses and reduced nozzle efficiency, further limiting performance.

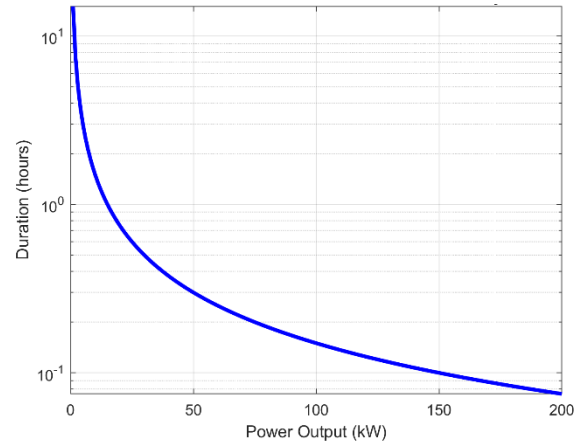


Figure 3: Power–duration characteristics of the DFES system at a nominal pressure of 10 atm and an overall efficiency of 64%

The curve shows that discharge time decreases as output power increases. Representative points include 10 kW (approximately 6.75 hours) and 100 kW (approximately 30 minutes).

Optimal Fluid Distribution

The analysis indicates that system performance is strongly influenced by the initial distribution of air and water within the storage tank. An initial water fraction of about 52% was found to maximize the usable energy output. This value remains nearly unchanged across the range of operating pressures considered.

The observed optimum can be explained by the balance between the two working fluids. When the water fraction is too low, the available hydraulic energy is limited, reducing power output. On the other hand, excessive water volume reduces the space available for compressed air, thereby decreasing the total energy that can be stored. The optimal point represents a balance between these competing effects.

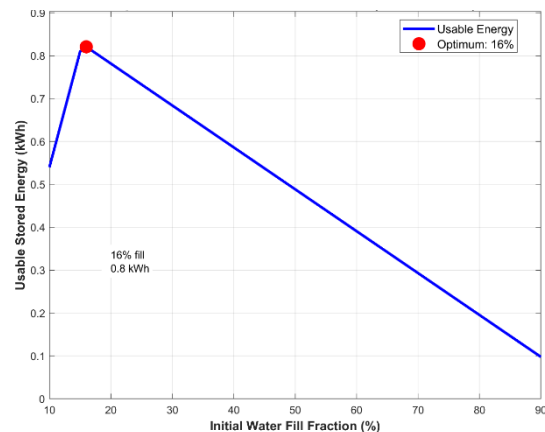


Figure 4: Variation of usable energy with initial water fill fraction for a 10 m³ tank at 10 atm

The peak in the curve occurs near 52%, indicating the most efficient distribution between air and water. This optimal

value shows minimal sensitivity to changes in operating pressure.

Comparison with Alternative Systems

A comparison with other mechanical energy storage methods highlights the advantages of the proposed system in terms of energy density. Under the same volume and pressure conditions, the dual-fluid configuration stores significantly more energy per unit volume than both bladder accumulators and gravity-based systems.

While gravity storage offers a simple and durable solution, its energy density is extremely low unless very large structures are used. Bladder accumulators provide faster response but suffer from reduced effective volume due to the presence of the separating membrane. Table 3: summarizes the comparison of usable energy and volumetric energy density for the three configurations

Table 3: Comparison of usable energy and volumetric energy density for the three configurations

Configuration	Usable Energy (kWh)	Energy Density (kWh/m ³)	Remarks
DFES (proposed system)	15.0	1.50	64% efficiency, 10 m ³ tank
Bladder accumulator	5.2	0.52	Reduced usable volume due to bladder
Gravity storage	≈ 0.027	0.0027	Based on 10-ton mass and 10 m lift

Overall, the DFES system achieves roughly three times the energy density of a bladder accumulator under comparable conditions. In contrast, gravity-based storage would require substantially larger physical dimensions to reach similar energy levels, making it less practical in space-constrained applications.

Discussion

Interpretation of Findings

The efficiency level obtained in this analysis falls within the range typically reported for small-scale compressed air energy storage systems that operate without fuel-based heating [35,36]. While it is possible to achieve higher efficiencies by incorporating thermal energy recovery, such modifications generally increase system complexity and may introduce additional technical challenges.

Another important outcome is the determination of an optimal water fill fraction that remains nearly constant across different operating pressures. This finding offers a useful design reference and highlights a parameter that has received limited attention in earlier studies.

Conclusion

This study examined the performance of a dual-fluid compressed air energy storage system as a non-combustion alternative for supporting renewable energy integration. Using a thermodynamic modeling approach and dynamic simulation, the system's behavior was evaluated under practical operating conditions. The results show that, for a storage volume of 10 m³ at 10 atm, the system can deliver approximately 15 kWh of usable energy with an overall efficiency of about 64%. In addition, the configuration demonstrates a clear advantage in volumetric energy density when compared with conventional hydraulic accumulators.

A key outcome of the analysis is the identification of an optimal initial water fraction near 52%, which remains relatively stable across different pressure levels. This parameter provides a practical reference point for system design and optimization. The relationship between discharge power and duration follows expected energy constraints, allowing predictable operation depending on demand requirements.

It should be emphasized that these findings are based on simulation results and have not yet been validated experimentally. Before practical deployment can be considered, further work is needed to confirm system performance under real operating conditions. This includes the development of a laboratory-scale prototype, along with detailed economic evaluation through life cycle cost analysis and environmental assessment using life cycle methodologies [46-50].

Future research may also explore design improvements to enhance system efficiency and flexibility. Potential directions include the incorporation of heat recovery to reduce thermal losses, coupling with solar thermal systems to mitigate cooling during expansion, and the use of advanced control strategies for regulating flow and output power. Together, these efforts would contribute to a more comprehensive understanding of the system's feasibility and its role in future energy systems.

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