



PERFORMANCE AND TECHNO-ECONOMIC EVALUATION OF A HYBRID FLOATING PHOTOVOLTAIC SYSTEM WITH MICRO-CAES

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ABSTRACT

The increasing deployment of floating photovoltaic systems has intensified the need for reliable and cost-effective energy storage solutions to mitigate intermittency. This study presents a hybrid floating photovoltaic system integrated with micro-compressed air energy storage and evaluates its thermodynamic performance and long-term economic feasibility under different climatic conditions. A coupled numerical framework combining thermodynamic modeling, climate-dependent performance simulation, and energy dispatch control was developed using ANSYS and MATLAB/Simulink environments. The round-trip efficiency of the storage subsystem was determined based on compressor and expander isentropic efficiencies, while system performance was assessed for moderate, hot, and cold climate scenarios. The results indicate that climatic conditions significantly affect compression work and overall storage efficiency, with round-trip efficiency varying between 41% and 47%. The proposed configuration demonstrates stable load support capability and improved reliability compared to battery-based alternatives in long-term operation. A 20-year techno-economic assessment incorporating capital expenditure, operational costs, replacement intervals, and a 7% discount rate shows competitive leveled cost of energy values relative to conventional storage technologies. The findings confirm that hybrid floating photovoltaic systems combined with micro-compressed air energy storage can provide a technically viable and economically sustainable solution for distributed renewable energy applications.



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1. INTRODUCTION

The global transition toward renewable energy systems has significantly accelerated the deployment of photovoltaic technologies in recent years [1] [2]. Among emerging configurations, floating photovoltaic (FPV) systems have gained increasing attention due to their ability to utilize unused water surfaces, reduce land occupation, and improve module performance through natural cooling effects [3-5]. By lowering panel temperature, floating platforms enhance conversion efficiency and mitigate thermal degradation compared to conventional ground-mounted systems [6] [7]. Recent studies have also emphasized the influence of water temperature and environmental conditions on the thermal and electrical characteristics of floating photovoltaic installations [8] [9]. Despite these advantages, floating photovoltaic systems remain inherently intermittent and require appropriate energy storage solutions to ensure stable power supply and improved load management under variable operating conditions [1] [2]. Energy storage technologies therefore play a critical role in compensating for renewable generation variability and enhancing system reliability. Among available storage technologies, compressed air energy storage (CAES) has been recognized as a promising alternative due to its relatively long service life, reduced dependence on scarce materials, and suitability for medium- and large-scale applications [10] [11]. Conventional diabatic CAES systems typically operate with round-trip efficiencies in the range of 42–54%, while adiabatic configurations may achieve higher efficiencies at the expense of increased system complexity [12] [13].

In distributed renewable systems, micro-scale CAES solutions have attracted attention as flexible and modular storage options suitable for hybrid photovoltaic configurations [14] [15]. Experimental and modeling studies confirm the feasibility of small-scale CAES under various thermodynamic and operational conditions [16–18]. Several techno-economic analyses have evaluated photovoltaic systems integrated with compressed air storage [19] [20]. However, most available investigations consider either floating photovoltaic performance independently or storage system performance separately. The combined thermodynamic interaction between floating photovoltaic temperature behavior and micro-scale CAES operation under varying climatic conditions remains less comprehensively addressed in distributed renewable applications. The present study develops an integrated modeling framework for a hybrid floating photovoltaic system combined with micro-compressed air energy storage under moderate, hot, and cold climatic scenarios. The approach includes temperature-dependent photovoltaic modeling, quasi-isentropic thermodynamic analysis of the compression–expansion cycle, hourly energy dispatch simulation, and long-term lifecycle economic assessment based on levelized cost of energy methodology [21]. The objective of this study is to evaluate the technical and economic performance of the proposed hybrid configuration over a 20-year operational horizon using a coupled ANSYS and MATLAB/Simulink simulation environment. Particular attention is given to the influence of ambient temperature on compression work, round-trip efficiency, system reliability, and economic indicators. The results indicate that climatic variations affect storage thermodynamics and overall system performance, with round-trip efficiency ranging between 41% and 47% across the analyzed scenarios. The hybrid FPV–micro-CAES configuration demonstrates stable load support capability and competitive lifecycle economic performance, suggesting its applicability in distributed renewable energy systems.

II. THEORETICAL REFERENCE

II.1 FLOATING PHOTOVOLTAIC THERMAL BEHAVIOR

Floating photovoltaic systems differ from conventional ground-mounted installations due to enhanced convective heat exchange between the module rear surface and the underlying water body. Several experimental investigations have confirmed that module operating temperature in floating configurations is typically reduced by 3–7 °C compared to land-based systems under similar irradiance conditions [3] [6] [7]. The electrical efficiency of photovoltaic modules is temperature-dependent and can be expressed as a linear correction relative to standard test conditions [22]. The temperature coefficient represents the rate of efficiency reduction per degree Celsius increase in cell temperature. Lower module temperature therefore directly improves electrical output and reduces long-term thermal degradation [5] [8]. Recent modeling studies have also demonstrated that water temperature, wind velocity, and system sizing influence the effective heat loss coefficient of floating photovoltaic modules [9]. These thermal interactions must be considered when evaluating integrated hybrid systems operating under different climatic conditions.

II.2 THERMODYNAMIC PRINCIPLES OF MICRO-COMPRESSED AIR ENERGY STORAGE

Compressed air energy storage operates on a compression–storage–expansion cycle. During periods of surplus generation, electrical energy is converted into mechanical compression work and stored as high-pressure air. During discharge, the stored air expands through a turbine to generate electricity [10] [11]. For a quasi-isentropic compression process, the required compression work depends on inlet temperature, pressure ratio, and compressor efficiency [14]. Similarly, the expansion process is influenced by turbine isentropic efficiency and thermal conditions within the storage vessel [12] [13]. Thermodynamic analyses indicate that inlet air temperature significantly affects compression work and round-trip efficiency [16] [18]. Lower ambient temperatures reduce specific compression energy demand, while elevated temperatures increase the required work input. This temperature dependence becomes particularly relevant in distributed applications where environmental conditions vary seasonally. Advanced CAES concepts incorporating thermal energy recovery have been investigated in pilot-scale demonstrations [17]. However, small-scale distributed CAES systems are often designed with simplified quasi-isentropic assumptions to balance performance and economic feasibility [14] [15].

II.3 TECHNO-ECONOMIC EVALUATION FRAMEWORK

The long-term economic performance of hybrid renewable systems is commonly assessed using the levelized cost of energy (LCOE) methodology [21]. LCOE accounts for capital expenditure, operational costs, discount rate, and lifetime energy production over a defined operational horizon. Previous techno-economic analyses of photovoltaic systems integrated with compressed air storage have demonstrated that lifecycle cost competitiveness depends strongly on capital expenditure and system utilization rate [19] [20–23]. In distributed applications, storage durability and reduced replacement frequency may provide long-term economic advantages compared to electrochemical alternatives [11]. Given the combined thermal behavior of floating photovoltaic systems and the temperature-dependent thermodynamics of micro-CAES, an integrated modeling approach is required to evaluate technical performance and economic indicators under varying climatic scenarios.

III. MATERIALS AND METHODS

The proposed hybrid system integrates a floating photovoltaic (FPV) array with a micro-compressed air energy storage (micro-CAES) subsystem and an energy dispatch control module. The architecture is designed for distributed renewable energy applications requiring stable load supply under variable climatic conditions [3] [10] [15]. The system consists of:

- Floating photovoltaic array installed on a water surface platform
- Air compressor and high-pressure storage vessel
- Expansion turbine coupled with a generator
- Inverter and control system for load management

The overall system architecture and energy flow pathways are illustrated in Fig. 1.

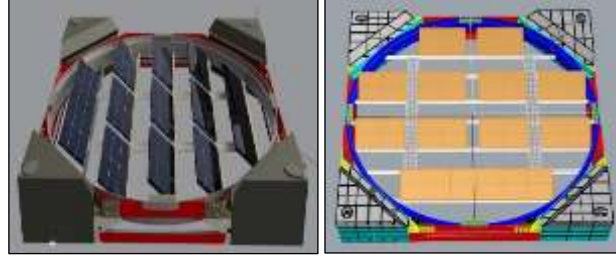


Figure 1: Floating system for solar energy generation and storage.

Source: Authors, (2026).

The floating configuration enhances convective heat transfer between the module rear surface and the water body, reducing module operating temperature compared to conventional ground-mounted systems [24]. The instantaneous photovoltaic output power is calculated as:

$$P_{PV}(t) = G(t) \cdot A \cdot \eta_{PV}(T_c) \quad (1)$$

Where $G(t)$ is solar irradiance (W/m^2), A is total active surface area (m^2), and $\eta_{PV}(T_c)$ is temperature-dependent conversion efficiency [22]. The temperature correction factor is defined as:

$$\eta_{PV}(T_c) = \eta_{ref} [1 - \beta(T_c - T_{ref})] \quad (2)$$

Where $\eta_{ref} = 0.18$, $\beta = 0.0045^\circ\text{C}^{-1}$, and T_c is the cell temperature ($^\circ\text{C}$) [4-7]. Module temperature is estimated through a heat balance model accounting for ambient temperature and enhanced convective cooling due to the floating configuration. The principal technical parameters adopted in the photovoltaic modeling are summarized in Table 1.

Table 1: Technical parameters of the floating photovoltaic subsystem.

Parameter	Value	Unit
Installed capacity	50	kW
Panel efficiency	18	%
Temperature coefficient	0.0045	$^\circ\text{C}^{-1}$
Nominal operating temperature	45	$^\circ\text{C}$
Annual degradation rate	0.7	%

Source: Authors, (2026).

The micro-CAES subsystem operates between predefined pressure limits and is modeled as a quasi-isentropic compression–expansion cycle [12-14]. The compression work is calculated as:

$$W_{comp} = \frac{\dot{m} c_p T_1}{\eta_c} \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] \quad (3)$$

The expansion work is:

$$W_{exp} = \dot{m} c_p T_3 \eta_t \left[1 - \left(\frac{P_4}{P_3} \right)^{\frac{k-1}{k}} \right] \quad (4)$$

Where: $\dot{m} = 0.12 \text{ kg/s}$ (mass flow rate), $c_p = 1.005 \text{ kJ/kgK}$, $k = 1.4$ (specific heat ratio), $\eta_c = 0.80$ (compressor efficiency), $\eta_t = 0.85$ (turbine efficiency)

The round-trip efficiency is defined as [10-25]:

$$\eta_{RT} = \frac{W_{exp}}{W_{comp}} \quad (5)$$

The main operational parameters of the micro-CAES subsystem used in the simulations are summarized in Table 2.

Table 2: Micro-CAES operational parameters.

Parameter	Value	Unit
Storage volume	15	m^3
Pressure range	5–30	bar
Compression ratio	6	–
Compressor efficiency	0.80	–
Turbine efficiency	0.85	–

Source: Authors, (2026).

Thermodynamic simulations were performed using ANSYS Fluent (ANSYS Inc., USA). A time-step simulation model with hourly resolution was implemented in MATLAB/Simulink (MathWorks, USA). At each time step:

- If photovoltaic production exceeds load demand, surplus energy is directed to compression.
- If photovoltaic production is insufficient, stored compressed air is expanded to support the load.
- If storage pressure reaches the lower operating limit, unmet demand is recorded.

The storage state of charge (SOC) is expressed as:

$$SOC = \frac{P_{current} - P_{min}}{P_{max} - P_{min}} \quad (6)$$

System reliability is evaluated using the loss of load probability (LOLP):

$$LOLP = \frac{\sum E_{unmet}}{\sum E_{demand}} \quad (7)$$

Three representative climatic scenarios were modeled: moderate, hot, and cold environments [21-26]. Before modeling the thermodynamic and photovoltaic performance under different environmental conditions, representative climatic input values were defined. The adopted climatic scenarios are summarized in Table 3.

Table 3: Climatic input parameters.

Scenario	Avg. temperature	Irradiance	Description
Moderate	20°C	850 W/m ²	Reference
Hot	35°C	1000 W/m ²	High solar
Cold	5°C	650 W/m ²	Winter

Source: Authors, (2026).

Ambient temperature influences:

- PV conversion efficiency
- Air density
- Compression work

A 20-year operational horizon was considered for economic evaluation. The levelized cost of energy (LCOE) was calculated as:

$$LCOE = \frac{\sum_{t=1}^{20} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{20} \frac{E_t}{(1+r)^t}} \quad (8)$$

Where $r = 7\%$ is the discount rate. The economic assumptions used for the long-term techno-economic assessment are consistent with approaches commonly adopted in hybrid renewable and multi-energy system studies [27]. The corresponding parameters are presented in Table 4.

Table 4: Economic parameters.

Parameter	Value	Unit
CAPEX (FPV)	950	USD/kW
CAPEX (CAES)	600	USD/kW
OPEX	2	% of CAPEX/year
Lifetime	20	years
Discount rate	7	%

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

Thermodynamic simulations demonstrate that ambient temperature significantly influences compression work and overall storage efficiency. Under hot climate conditions (average 35°C), the inlet air temperature increases the required compression work by approximately 8–12% compared to moderate conditions. Conversely, cold climate conditions (5°C) reduce compression energy demand by approximately 10%, improving thermodynamic performance. The calculated round-trip efficiency varies between 41% and 47% depending on climatic scenario. The highest efficiency ($\approx 47\%$) is observed in cold conditions due to lower compression work, while hot climate conditions reduce efficiency to approximately 41–42%. The variation of round-trip efficiency as a function of ambient temperature is illustrated in Fig. 2.

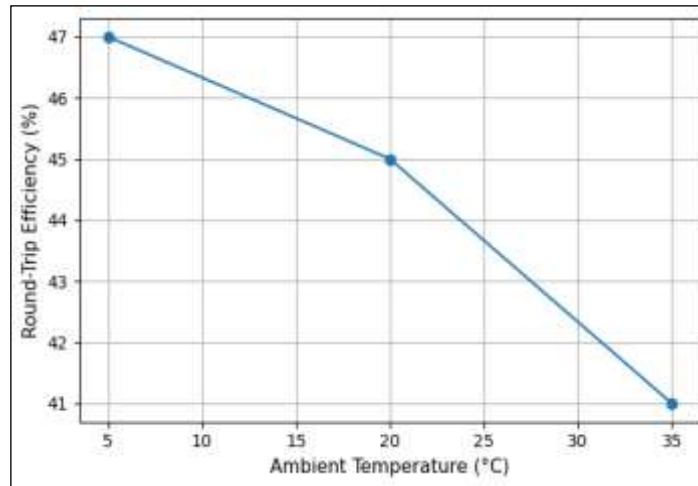


Figure 2: Round-trip efficiency variation under different climatic scenarios.

Source: Authors, (2026).

These results confirm that temperature-dependent air density and compressor inlet conditions play a critical role in distributed CAES performance [28] [29]. Although micro-scale systems operate under simplified thermodynamic assumptions, environmental temperature variations noticeably affect overall energy conversion efficiency. The floating configuration demonstrates improved thermal stability compared to conventional ground-mounted systems. Under elevated ambient temperature conditions, increased module temperature in land-based systems results in measurable efficiency reduction. In contrast, floating installations benefit from enhanced convective heat exchange with the water surface, which mitigates thermal losses. The comparative hourly photovoltaic power output profiles for moderate climate (floating), hot climate (ground-mounted), and hot climate (floating configuration) are presented in Fig. 3.

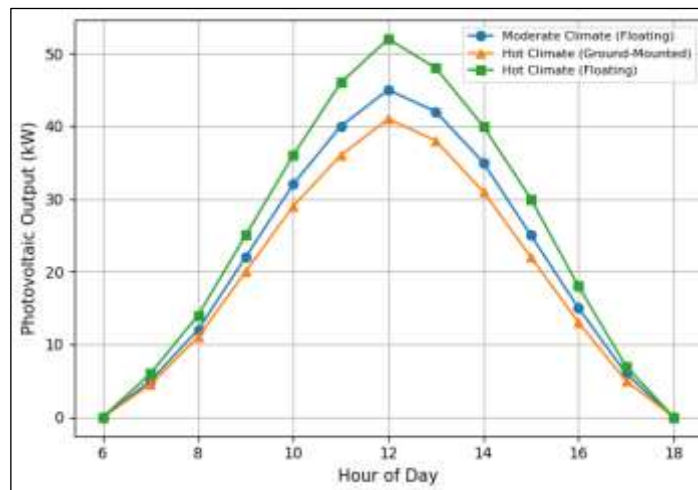


Figure 3: Photovoltaic power output profiles under moderate and hot climatic conditions demonstrating the cooling effect of floating installation.

Source: Authors, (2026).

As shown in Fig. 3, the floating system under hot climatic conditions produces approximately 8–12% higher peak output compared to the ground-mounted configuration due to reduced module temperature. The average temperature reduction of 3–5°C results in an increase of photovoltaic efficiency by approximately 1.5–2%. Over annual operation, floating configurations yield approximately 4% higher energy production relative to equivalent land-based systems operating under identical irradiance conditions. While this increase is moderate, it contributes positively to overall system performance and lifecycle economics. The energy management algorithm ensures priority supply to load demand, with surplus photovoltaic energy directed toward compression. Simulation results indicate that the hybrid FPV–micro-CAES configuration maintains stable load support under all modeled climatic scenarios. The calculated loss of load probability (LOLP) remains below 2% for moderate and hot climates, while slightly higher values (approximately 3%) are observed under cold conditions due to seasonal reduction in photovoltaic output. The quantitative reliability indicators obtained from the simulations are summarized in Table 5.

Table 5: Reliability indicators under different climatic scenarios.

Scenario	Round-trip efficiency (%)	LOLP (%)	Annual energy supplied (MWh)
Moderate	45	1.8	82
Hot	41	1.6	88
Cold	47	3.0	75

Source: Authors, (2026).

As shown in Table 5, although cold climates improve thermodynamic storage efficiency, reduced solar availability slightly increases the probability of unmet load. In contrast, hot climates exhibit lower reliability risk due to higher annual photovoltaic generation, despite reduced storage efficiency. Overall, the results indicate that climatic conditions influence thermodynamic performance, photovoltaic output, and reliability metrics in different ways. The combined evaluation highlights the importance of integrated assessment when designing distributed hybrid renewable systems. The long-term economic evaluation conducted over a 20-year operational period indicates that although the initial capital expenditure of the micro-CAES subsystem is higher than that of typical battery storage systems, lifecycle replacement costs are significantly lower due to the absence of frequent component degradation and replacement cycles. The calculated levelized cost of energy (LCOE) values under different climatic scenarios are:

- Moderate climate: 0.087 USD/kWh
- Hot climate: 0.082 USD/kWh
- Cold climate: 0.094 USD/kWh

The comparative LCOE results are presented in Fig. 4, where the scenarios are arranged in ascending order of cost to facilitate relative comparison.

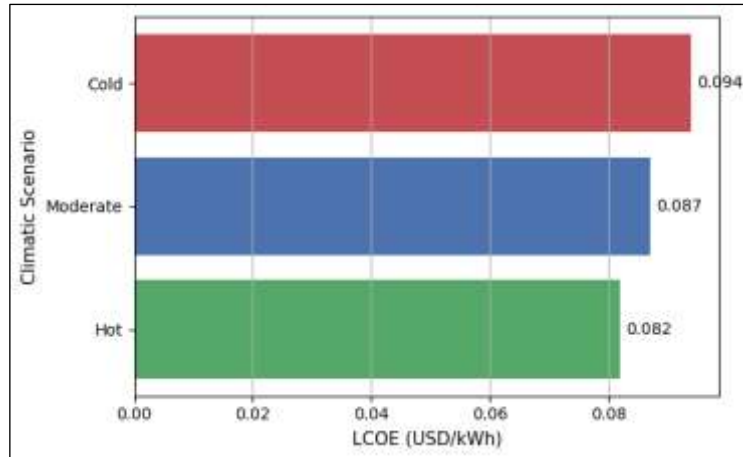


Figure 4: Levelized cost of energy (LCOE) under different climatic scenarios over a 20-year operational horizon.
Source: Authors, (2026).

As shown in Fig. 4, the hot climate scenario exhibits the lowest LCOE (0.082 USD/kWh), followed by the moderate (0.087 USD/kWh) and cold (0.094 USD/kWh) scenarios. This ordering reflects the influence of annual photovoltaic energy yield on lifecycle cost indicators. Although cold conditions improve storage thermodynamic efficiency, reduced solar irradiance limits total annual energy production, resulting in slightly higher LCOE values. Battery-based storage systems, when evaluated under similar operational assumptions, require multiple replacement cycles within a 20-year horizon. This increases cumulative lifecycle cost by approximately 18–22% compared to the proposed micro-CAES configuration. Consequently, the hybrid FPV–micro-CAES system demonstrates competitive long-term economic performance for distributed renewable applications. To evaluate the robustness of the proposed system, a sensitivity analysis was performed considering variations in capital expenditure, compressor efficiency, and photovoltaic efficiency. The resulting impact on LCOE is illustrated in Fig. 5, where the influencing factors are ordered according to their relative magnitude of effect.

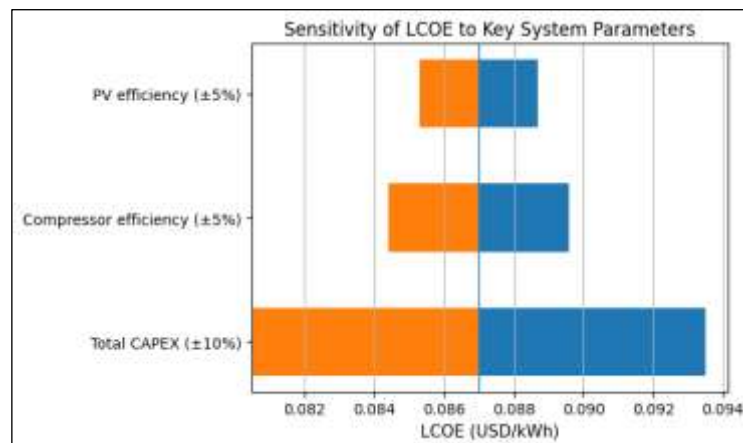


Figure 5: Tornado sensitivity analysis of LCOE with respect to key system parameters (base case LCOE = 0.087 USD/kWh).
Source: Authors, (2026).

As shown in Fig. 5, capital expenditure represents the most influential parameter affecting lifecycle economic performance. A 10% increase in total CAPEX results in an approximate 6–8% increase in LCOE. In contrast, a 5% improvement in compressor efficiency reduces LCOE by approximately 3%. Variations in photovoltaic efficiency produce a moderate but noticeable impact.

These results suggest that cost optimization strategies should prioritize capital cost reduction and hardware efficiency improvements to enhance economic competitiveness. The obtained results confirm that climatic conditions simultaneously influence thermodynamic storage performance and photovoltaic generation efficiency. Cold ambient conditions improve compression performance and increase round-trip efficiency to approximately 47%. However, reduced solar resource availability limits annual energy yield and slightly increases LCOE. Conversely, hot climates reduce compression efficiency but benefit from higher solar irradiance, resulting in the lowest lifecycle cost among the evaluated scenarios. These findings are consistent with previous thermodynamic analyses of CAES systems, which highlight the influence of inlet temperature on compression work and overall efficiency [10] [30] [31]. In addition, the observed cooling effect of floating photovoltaic systems aligns with experimental studies reporting measurable temperature reductions in FPV installations under real climatic conditions [6] [7]. Unlike large-scale CAES plants analyzed in prior research, the present study focuses on distributed micro-scale applications, where climatic effects influence both photovoltaic thermal behavior and storage thermodynamics simultaneously. The integrated modeling framework therefore enables a coupled assessment of technical and economic performance under climate-sensitive operating conditions. From an economic perspective, the obtained LCOE values (0.082–0.094 USD/kWh) fall within the competitive range reported for hybrid renewable systems with integrated storage [19] [20] [32]. Although micro-CAES exhibits lower round-trip efficiency than electrochemical batteries, its extended service life and reduced replacement frequency provide an economic advantage over long-term operation. Overall, the integration of floating photovoltaic systems with micro-compressed air energy storage represents a technically feasible and economically competitive configuration for decentralized renewable energy systems. The results emphasize that climatic adaptability should be considered not only in photovoltaic performance analysis but also in storage thermodynamics and lifecycle economic evaluation.

V. CONCLUSIONS

This study presented a thermodynamic and techno-economic evaluation of a hybrid floating photovoltaic system integrated with micro-compressed air energy storage under varying climatic conditions. The developed modeling framework combined temperature-dependent photovoltaic analysis, quasi-isentropic compression–expansion modeling, energy dispatch simulation, and long-term lifecycle economic assessment over a 20-year operational period. The results showed that ambient temperature influences compression work and storage efficiency, with round-trip efficiency ranging between 41% and 47% across the analyzed climatic scenarios. The floating photovoltaic configuration reduced module temperature by approximately 3–5 °C, contributing to improved electrical output compared to ground-mounted systems. The lifecycle economic analysis indicated competitive levelized cost of energy values between 0.082 and 0.094 USD/kWh, with capital expenditure identified as the dominant economic driver. Overall, the proposed FPV–micro-CAES configuration represents a technically feasible and economically competitive option for distributed renewable energy applications, particularly in regions with favorable solar conditions. Further research may address advanced thermal recovery integration and pilot-scale validation to enhance system efficiency and operational performance.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Naciba Piriyeve and Sona Rzayeve.

Methodology: Naciba Piriyeve and Gulcshe Kerimzade.

Investigation: Gulcshe Kerimzade and Sona Rzayeve.

Discussion of results: Naciba Piriyeve, Sona Rzayeve and Gulcshe Kerimzade.

Writing – Original Draft: Naciba Piriyeve.

Writing – Review and Editing: Sona Rzayeve, Gulcshe Kerimzade and Arnawan Hasibuan.

Resources: Arnawan Hasibuan.

Supervision: Arnawan Hasibuan.

Approval of the final text: Najiba Piriyeve, Sona Rzayeve, Gulcshe Kerimzade, Nijat Mammadov, Arnawan Hasibuan.

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