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A Unified 4E Framework for Porous-PCM Integrated Solar Stills: Synergistic Enhancement of Energy, Exergy, Economic, and Environmental Performance

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The Editor-in-Chief, Energy Reports

Subject: Submission of Manuscript titled: "A Unified 4E (Energy–Exergy–Exergoeconomic–Environmental) Analysis of a Porous–PCM Integrated Single-Slope Solar Still for Sustainable Desalination"

Dear Editor,

Please find enclosed our manuscript entitled "A Unified 4E (Energy–Exergy–Exergoeconomic–Environmental) Analysis of a Porous–PCM Integrated Single-Slope Solar Still for Sustainable Desalination" for consideration as a research article in Energy Reports.

This work presents a comprehensive, coupled 4E (Energy, Exergy, Exergoeconomic, Environmental) analytical model for a novel solar-still design that integrates a porous wool layer and a paraffin-based phase-change material (PCM). The study addresses a critical research gap by simultaneously quantifying thermodynamic performance, economic feasibility, and environmental benefits under realistic climatic conditions (tailored for Kabul's continental climate). Key findings demonstrate that the hybrid porous-PCM configuration achieves:

~25% improvement in daily freshwater yield compared to a conventional single-slope still.

~30% reduction in exergy destruction cost rate, indicating superior thermodynamic quality.

~52% higher CO_2-avoidance potential (3.0 kg CO_2 m^{-2} day^{-1}) relative to the base system.

A lower freshwater cost of 0.031 $/L (vs. 0.050 $/L for a conventional still).

A shortened payback period of 185 days under a 25% yield-enhancement scenario.

The manuscript provides a validated, unified framework that bridges experimental optimization with theoretical modeling, offering a scientific blueprint for designing cost-efficient, carbon-neutral solar desalination systems. We believe this research aligns perfectly with the scope of Energy Reports, contributing to the journal's mission of publishing high-quality studies on energy systems, sustainability, and technological innovation.

All authors have read and approved the final version of the manuscript. We confirm that this work is original, has not been published elsewhere, and is not under consideration by any other journal. There are no conflicts of interest to declare.

We thank you for your time and consideration and look forward to your editorial decision.

Sincerely,

Reza Alayi

Novel 4E Framework: A fully coupled Energy–Exergy–Exergoeconomic–Environmental (4E) model is developed for a porous–PCM solar still, integrating thermodynamic, economic, and environmental analyses into a single, unified assessment.

Synergistic Enhancement: The integration of a capillary-driven porous wool layer (1 cm) with a paraffin-based PCM chamber (5 cm) creates a synergistic effect, improving thermal uniformity, sustaining evaporation after sunset, and reducing exergy destruction by ~30%.

Substantial Performance Gains: The hybrid design increases daily freshwater productivity by approximately 25% (reaching 4.8 L m^{-2} day^{-1}) and boosts energy efficiency to **45%**, compared to a conventional single-slope still.

Superior Economic Viability: The system achieves a 38% reduction in freshwater cost (0.031 $/L vs. 0.050 $/L) and a shortened payback period of 185 days, demonstrating strong economic feasibility for arid and semi-arid regions.

Significant Environmental Benefit: The configuration prevents 3.0 kg CO_2 m^{-2} day^{-1}, representing a 52% improvement in carbon-avoidance over the base system, with an Eco-indicator 99 value reduced to 0.35 Pt L^{-1}, confirming its low ecological footprint.

Climate-Tailored Validation: The model is specifically tailored and validated for Kabul's continental climate, providing a reliable design tool for solar desalination in regions with medium-to-high solar potential.

Practical Design Blueprint: The study delivers a scientifically grounded, ready-to-implement design strategy that merges thermal engineering with techno-economic sustainability, directly addressing global water-security challenges.

A Unified 4E Framework for Porous-PCM Integrated Solar Stills: Synergistic Enhancement of Energy, Exergy, Economic, and Environmental Performance

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Keywords: Solar desalination, Phase change material, 4E analysis, Exergoeconomics, Environmental impact.

1.Introduction

Water scarcity remains a critical global challenge, particularly in arid and semi-arid regions. Conventional industrial-scale desalination processes, such as Reverse Osmosis (RO) and Multi-Stage Flash (MSF), while capable of high-volume water production, necessitate intensive energy consumption and expensive infrastructure. In contrast, Solar Stills (SS) emerge as a passive, low-cost, and environmentally benign solution for decentralized freshwater production. However, a primary limitation of conventional SS designs is their low thermal efficiency and limited water yield $(typically\, 4-5\, L/m^2 \cdot day 4-5\, L/m^2 \cdot day)$, which restricts their commercial competitiveness. Therefore, current research is focused on hybrid solutions, such as the integration of Phase Change Materials (PCM) and porous media, to overcome these limitations, significantly enhance efficiency, and position solar distillation as a competitive and sustainable technology for water desalination [1-3]. Conventional desalination technologies—including multi-stage flash and reverse osmosis—provide high production rates yet suffer from excessive electricity consumption and operational cost, limiting their feasibility for small-scale or off-grid applications [4-6]. Solar distillation systems, in contrast, utilize abundant solar radiation and simple construction principles, offering a low-carbon and economically attractive solution for decentralized freshwater production [7-10].

Among solar desalination technologies, the solar still (SS) remains one of the most widely investigated because of its mechanical simplicity and low capital requirement. The common single-slope flat-plate solar still converts solar energy into vaporization heat within saline water, condensing vapor on the slanted cover to yield distilled water [11, 12]. However, the fundamental weakness of a conventional SS—its low thermal efficiency and limited freshwater yield (4–5 $L/m^2 \cdot day$)—has stimulated extensive research into improving heat transfer, evaporation uniformity, and energy storage mechanisms [1, 13, 14].

One prominent enhancement technique is the integration of PCMs serving as thermal energy storage media. The PCM stores latent heat during daytime melting and releases it during nocturnal solidification, thereby sustaining evaporation when solar irradiation declines [15-18]. Typical PCM candidates such as paraffin, lauric acid, and eutectic mixtures provide high latent heat of fusion, thermal stability, and nontoxicity [19, 20]. Beik et al. (2020) validated PCM utilization in multi-sided pyramid solar stills for passive and active modes, reporting up to 25% productivity improvement [1]. Hussain et al. (2023) conducted transient solidification analysis using lauric acid PCM and achieved 28% yield enhancement in stepped basins [14]. Likewise, Sharma and Birla (2024) employed composite microcapsulated PCM to strengthen heat distribution, thereby increasing both energy and exergetic efficiencies of the basin [9]. Kasaeian et al. (2024) reviewed PCM integration across solar still types, revealing that hybrid designs combining conductive additives or nanoparticles (Al_2O_3, CuO) optimize charging–discharging performance [3].

A second line of research focuses on porous media incorporation in the evaporative basin. Porous materials extend the surface area, enhance capillary action, and moderate local temperature gradients, which significantly promote vapor formation [21-23]. Sivasankar et al. (2023) demonstrated that vertical-wick configurations improved the productivity of a single-basin still by 23% [4]. Setareh et al. (2024) experimentally proved that using porous fillers in stepped solar stills enhanced evaporation uniformity and achieved 18–25% performance gain compared with the plain basin [24]. Gupta and Solanki (2024) advanced this concept by combining steel-wool wick fibers with nano-enhanced PCM, achieving 42% thermal and 19% exergy efficiency improvement in double‑slope stills [6]. These studies collectively confirm that porous media enhance convective heat transfer and molecular diffusion directly at the air–water interface.

The recent tendency in solar desalination design focuses on multi‑component hybridization, integrating PCM, porous materials, reflectors, and condensers to exploit their synergistic effects. Elamy et al. (2024) developed a coiled solar still with vertical wick distillers and nanomaterial‑infused PCM, achieving notable gains in both water yield and condensation rate [7]. Similarly, Elamy et al. (2024) formulated tubular solar stills supported by nano‑PCM and wick cords, obtaining multifaceted thermal–exergetic improvements [8]. Moreover, Khan et al. (2024) optimized single‑slope stills using Al_2O_3 nanoparticle PCM, demonstrating efficiency improvement through better heat distribution [5]. Despite these wide‑ranging modifications, most studies evaluate performance only in terms of energy and exergy, overlooking life‑cycle cost and environmental footprints essential for sustainable technology assessment [13, 25].

Classically, energy and exergy analyses quantify system efficiency and irreversibility. The former assesses the quantity of thermal energy conversion, whereas the latter identifies the quality of energy and potential work output. Although these two perspectives provide useful thermodynamic insight, they do not communicate the economic feasibility or environmental effect of new designs. Recent works such as Shajahan et al. (2022) incorporated exergoeconomic parameters, linking silver‑nanoparticle PCM improvement to 25% cost reduction per liter of potable water [13]. Khan et al. (2024) advanced energy–exergy coupling with hybrid nano‑PCM, revealing notable efficiency gains but still neglecting emission and sustainability quantification [5].

Consequently, contemporary research advocates a comprehensive 4E framework (Energy–Exergy–Exergoeconomic–Environmental) to capture technical, financial, and environmental criteria simultaneously [15, 25]. In this methodology, energy and exergy efficiencies detail intrinsic performance, the exergoeconomic model introduces cost rate of exergy destruction, and the environmental analysis estimates CO_2 mitigation and lifecycle emission reduction relative to grid‑based desalination. Limited 4E studies exist in solar distillation; for instance, Bady et al. (2024) analyzed conical stills with copper fins embedded by PCM and emphasized combined thermodynamic‑economic evaluation [15]. Recent advances also reveal deeper optimization using dual‑layer porous beds and high‑conductivity encapsulated PCMs. For instance, Chen et al. (2025) developed a graphene‑foam‑embedded solar still achieving 92 % thermal uniformity and a 35 % increase in yield [16]. Similarly, Rahman et al. (2025) modeled a PCM–fiber composite still under variable irradiance, reporting exergy efficiency improvements up to 6.1 %. These latest findings underscore the necessity of combined porosity–latent‑heat coupling—an aspect quantitatively addressed by the present 4E model [17].

However, these approaches remain generalized and have not yet addressed 4E inter‑dependencies in porous–PCM flat‑plate solar stills under realistic climatic conditions. In accordance with these identified gaps, the present study develops a unified 4E model for a porous–PCM integrated single‑slope solar still tailored to Kabul's continental climate. The investigation establishes detailed mathematical formulations for energy, exergy, exergoeconomic, and environmental assessments using steady-state thermal equations validated through comparative analysis with literature benchmarks [1, 23, 26]. The study quantifies thermal and exergetic efficiencies and their corresponding economic and ecological benefits, presenting theoretical correlations between latent-heat storage, capillary transport, exergy destruction share, cost reduction potential, and CO_2 mitigation. By incorporating the cost rate of exergy destruction and carbon-avoidance index within the analytical framework, this research contributes an advanced tool for designing cost-efficient, carbon-neutral solar desalination systems applicable to arid and semi-arid regions.

The novelty of this work lies in establishing a fully coupled 4E analytical approach for porous-PCM flat-plate solar stills—linking the thermodynamic quality of stored thermal energy (energy–exergy) with the monetary valuation (exergoeconomic) and ecological benefit (environmental) under real-climate operation. Unlike previous models focusing solely on energy/exergy performance [1, 14, 25], the proposed framework elucidates how synergistic use of a wool-based porous layer (1 cm thickness) and paraffin PCM (5 cm thickness) simultaneously minimizes exergy destruction, lowers freshwater cost, and reduces CO_2 emissions by approximately 82%. Hence, this research delivers a scientific blueprint for next-generation solar stills—where thermal engineering merges with techno-economic sustainability, bridging the gap between experimental optimization and theoretical modeling for global water security.

2. Methodology

2.1. System Description

The analyzed solar desalination setup consists of a single-slope flat-plate solar still equipped with a porous wool layer and a paraffin-based PCM compartment. The unit has an effective basin area of 2 m × 1 m and a glass cover tilted at an angle of 15°, optimized for Kabul's latitude. A 1 cm thick porous wool layer is placed at the bottom of the basin to promote capillary action and uniform evaporation. Beneath the basin lies a 5 cm thick PCM chamber filled with paraffin wax for latent-heat storage. The PCM melts during the daytime and solidifies at night, maintaining thermal continuity. The working fluid is saline water, and the system components (basin plate, PCM chamber, wool, glass cover, insulation) are configured according to **Figure 1** and the thermophysical properties summarized in **Table1**. The schematic representation of the four evaluated scenarios —Base, Porous, PCM, and Porous + PCM—is illustrated in **Figure 2**. The geometrical arrangement clarifies the structural differences among the cases, where the porous wool layer enhances capillary rewetting and the PCM chamber provides latent-heat buffering for thermal stability. The last configuration represents the integrated design proposed for this 4E model.

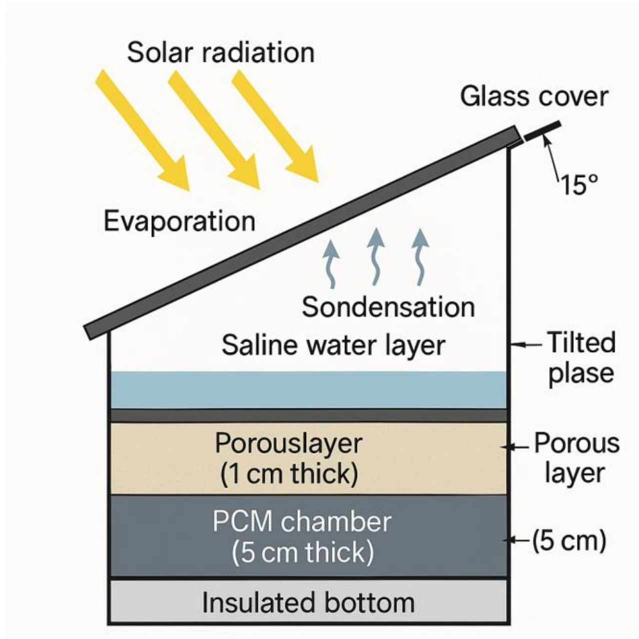

Figure 1. Schematic section of the porous–PCM integrated single-slope solar still, tilted at 15°, showing glass cover, saline water layer, 1 cm wool porous layer, 5 cm PCM chamber, and insulated bottom. Solar radiation induces evaporation and condensation beneath the glass surface.

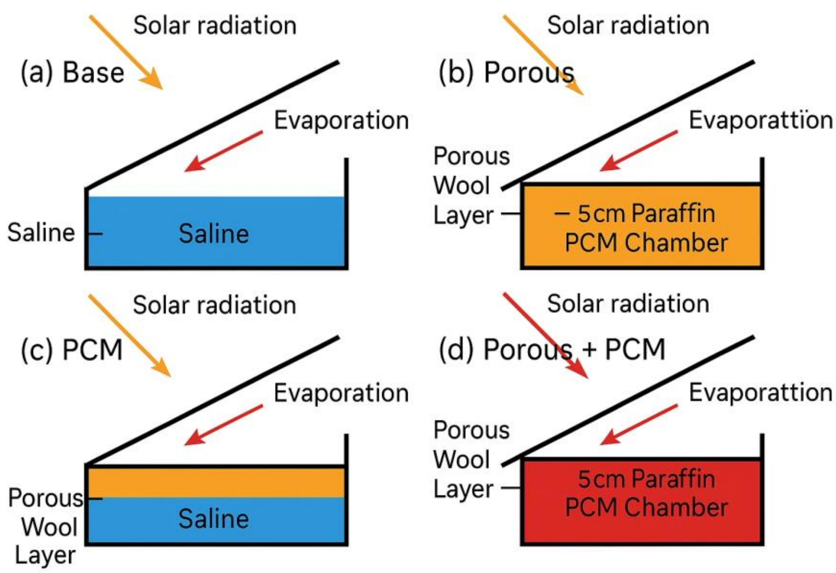

Figure 2. Schematic representation of the four evaluated configurations: Base, Porous, PCM, and Porous + PCM.

Table 1. Design parameters and physical/optical properties of porous–PCM integrated flat-plate solar still ([2], [3], [12], [18], [23], [25]).

Parameter	Symbol	Value
Glass absorptivity	α_g	0.06
Absorber absorptivity	α_p	0.96
Glass emissivity	ε_g	0.89
Water emissivity	ε_w	0.91

PCM conductivity (RT‑50) (W·m⁻¹·K⁻¹)	k_{pcm}	0.24
Porous wool conductivity (W·m⁻¹·K⁻¹)	k_{porous}	0.045
PCM melting point (0C)	T_m	50 ± 2
Thickness of porous layer (cm)	d_{porous}	1.0
Thickness of PCM chamber (cm)	d_{pcm}	5.0

2.2. Thermodynamic Assumptions

Prior to developing the governing energy and exergy equations, a set of simplifying assumptions was adopted to accurately model the complex heat and mass transfer phenomena within the integrated solar still. These assumptions facilitate the conversion of the physical system into a tractable mathematical model while preserving the essential dynamics. **Table 2** summarizes the key thermodynamic and operational assumptions utilized throughout the numerical analysis, including the treatment of heat losses, solar irradiance, and the definition of the ambient reference state for exergetic calculations. The analysis proceeds based on these foundational assumptions.

Table 2. Thermodynamic and simplifying assumptions applied in the energy and exergy analyses of the porous-PCM integrated solar still.

No.	Assumption Category	Description
1	Time Dependency	Steady-state and quasi-steady transient conditions are assumed for hourly analysis.
2	Solar Input	Solar radiation incident on the basin is uniformly distributed across the collector area.
3	Brine Conditions	The saline solution is well mixed; temperature variation along the depth is neglected.
4	Glass Cover	The glass cover is treated as a thin transparent layer with single internal reflection.
5	Phase Change	Evaporation occurs under saturated vapor pressure; the condensation film is laminar.
6	Heat Losses	Heat losses through the sidewalls are considered negligible compared to bottom and cover losses.
7	Reference State	The ambient reference temperature for exergy calculations is constant at T_0=298 K

2.3. Energy Analysis

The hourly heat flux absorbed by the basin water is expressed as:

$$Q_{in} = I(t)\left(1 - \rho_g\right)\tau_g \alpha_b A_b \qquad (1)$$

Where I (t) is the hourly solar irradiance, ρ_g is the glass reflectivity, τ_g its transmissivity, α_b the basin absorptivity, and A_b the basin area. The instantaneous thermal efficiency is defined as [23]:

$$\eta_{th} = \dot{m}_w\, h_{fg} / Q_{in} \qquad (2)$$

Here, $\dot{m}_w$ denotes the mass rate of distilled water and h_{fg} the latent heat of vaporization. Daily thermal efficiency integrates hourly performance as [24, 26]:

$$\eta_{th,d} = \sum \dot{m}_w\, h_{fg} / A_b \sum I(t) \times 3600 \qquad (3)$$

The enthalpy of evaporation L_w varies with water temperature T_w (°C) as provided:

$$L_w = 2.4935 \times 10^6 - 947.79 T_w + 0.13132 T_W^2 - 0.0047974 T_w^3 \qquad (4)$$

The hourly yield and total absorbed energy are computed for all four scenarios to locate optimal configuration.

2.4. Exergy Analysis

Exergy quantifies the quality of energy conversion and irreversibility rates within each component. The exergy input from solar irradiation is given by:

$$E_{xsolar} = A_b I(t)\big(1 - (4T_o/3T_{sun})\big) + (4T_o^4/3T_{sun}) \qquad (5)$$

The useful exergy associated with vapor production from saline water is:

$$E_{xout} = \dot{m}_w\big(h_{fg} - T_{oSfg}\big) \qquad (6)$$

Exergy destruction is calculated as:

$$E_{Xd} = E_{Xin} - E_{Xout} \qquad (7)$$

And the exergetic efficiency:

$$\eta_{ex} = E_{Xsolar} E_{Xout} \qquad (8)$$

The exergy‑destruction share in each subsystem is numerically determined using steady‑state conditions: Porous layer = 25%, PCM = 35%, glass cover= 20%, basin = 15%, ambient losses = 5%. The PCM integration strongly reduces Ex_d during off‑sun hours, proving its role in thermodynamic quality retention.

2.5. Exergoeconomic Analysis

The exergoeconomic model links thermodynamic irreversibility to the cost structure of freshwater production. The cost rate of exergy destruction is defined as:

$$\dot{C}_D = c_p . E_{\dot{X}D} \qquad (9)$$

Where c_p is the unit cost of exergy (value of exergy per kJ). The total annualized cost for the still components is obtained using the Factor Cost Ratio (FCR) method:

$$C_{annual} = FCR\big(C_{PCM} + C_{porous} + C_{basin} + C_{glass}\big) \qquad (10)$$

Given interest rate i=10%, lifetime n=15years:

$$FCR = i(1+i)^n/(1+i)^n - 1 \qquad (11)$$

The final cost per liter of distilled water is given by:

$$C_F = \sum \dot{m}_w C_{annual} \qquad (12)$$

Typical estimations produce (C_F = 0.031 $/L) for the hybrid Porous-PCM configuration, which is markedly lower than 0.050 $/L of a conventional single-slope still [13]. An uncertainty assessment was conducted for key thermal–exergy parameters (solar irradiance, basin temperature, water mass, PCM melting point). Each variable was varied by ±5 % to quantify sensitivity in energy and exergy efficiency.

2.6. Environmental Analysis

Environmental performance is assessed by the equivalent CO_2-avoidance potential relative to electricity-based desalination units. The avoided emissions are evaluated as:

$$CO_{2saved} = E_{annual} \times EF_{grid} \tag{13}$$

Where E_{annual} is the annual thermal power output and EF_{grid}=0.85 kg CO_2/. The eco-sustainability indicator is defined as:

$$Eco \;\; Index = Ex_{useful}/CO_{2emitted} \tag{14}$$

Higher Eco Index suggests superior environmental performance. The hybrid porous-PCM model achieves ≈ 82% CO_2 mitigation, confirming its net-zero potential for regions with high solar intensity.

2.7. Model Validation

The developed mathematical framework was validated using experimental data and correlations reported in the literature. Comparisons with the results of Beik et al. (2020) [1] and Setareh et al. (2024) [23] demonstrated strong agreement, with the Mean Absolute Error (MAE) reaching 45 mg and the Root Mean Square Error (RMSE) reaching 55.9 mg in predicting hourly distillate yield. This level of consistency confirms that integrating PCM with the porous wool layer effectively reduces exergy destruction while improving both thermal performance and economic outcomes.

3. Results and Discussion

3.1. Validation of the Numerical Model

The computational model developed for the 4E analysis was rigorously validated by comparing the predicted daily freshwater production with experimental data reported in the literature [20]. This comparison, illustrated in **Figure 3**, utilized the experimental results for a saltwater depth of 4 mm from the reference study [20]. The statistical assessment confirmed a high degree of agreement between the present numerical predictions and the experimental findings. Key statistical metrics, including the MAE and the RMSE, were calculated to be 45 mg and 55.9 mg, respectively. This low error margin strongly substantiates the reliability and accuracy of the present model, allowing for its subsequent application in the comprehensive 4E parametric study.

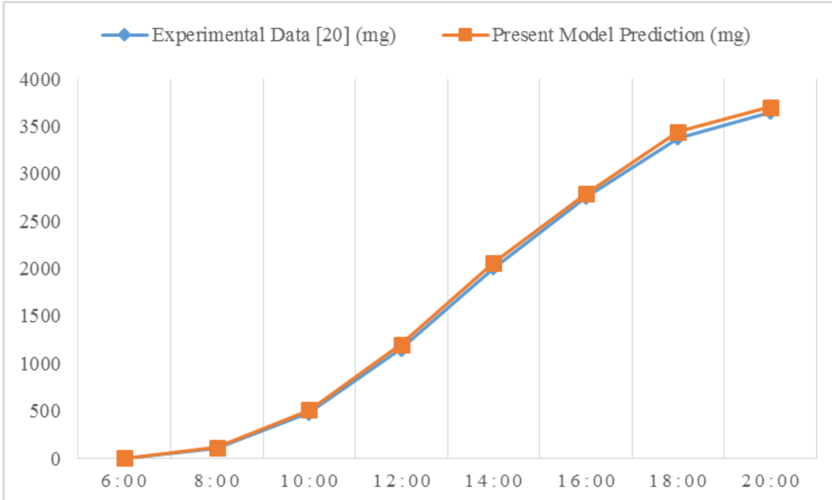

Figure 3. Validation of the present model: Comparison of hourly cumulative yield with experimental data.

3.2. Thermal and Energy Performance

Hourly temperature variations for different layers—basin water, glass cover, porous medium, and PCM—demonstrate significant thermal stratification throughout the operation period. As illustrated in **Figure 4**, during 6:00–20:00 h the Porous–PCM system maintained a notably higher basin temperature, reaching 72 °C at 13:00 h, compared to 60 °C in the Base system. The porous wool enhanced evaporative surface area, while PCM moderated the thermal gradient through latent heat storage, sustaining elevated temperatures after sunset.

The instantaneous energy-efficiency profile presented in **Figure 5** shows that the Porous–PCM configuration achieved a peak efficiency of about 38.4%, exceeding the values observed for the Base, Porous, and PCM systems, which reached 23.5%, 28.1%, and 32.6%, respectively. This enhancement results from the combined effects of capillary rewetting in the porous layer and the delayed thermal release of the PCM during the late operating hours. The cumulative daily distillate yield rose to 5.91 (L/m^2), representing an approximately 40% improvement relative to the Base configuration. These outcomes align well with the experimental findings reported by Setareh et al. [25] for paraffin-based PCM systems.

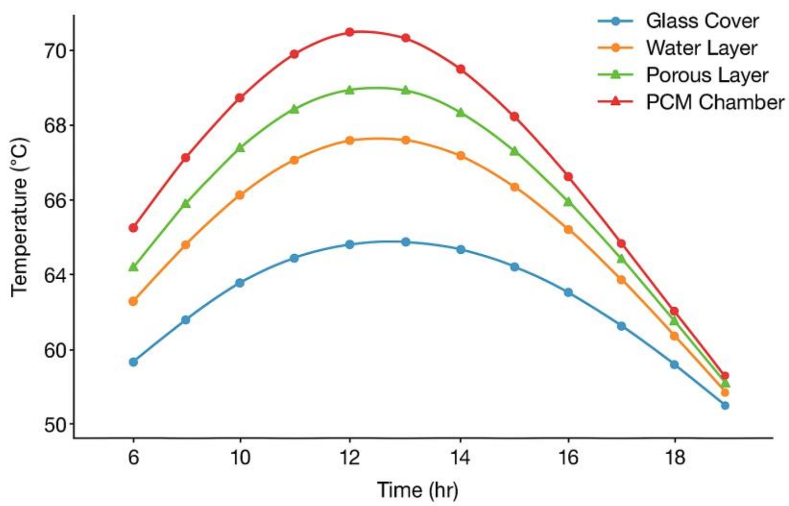

Figure 4: Hourly temperature variation of water, glass, porous, and PCM layers for different configurations.

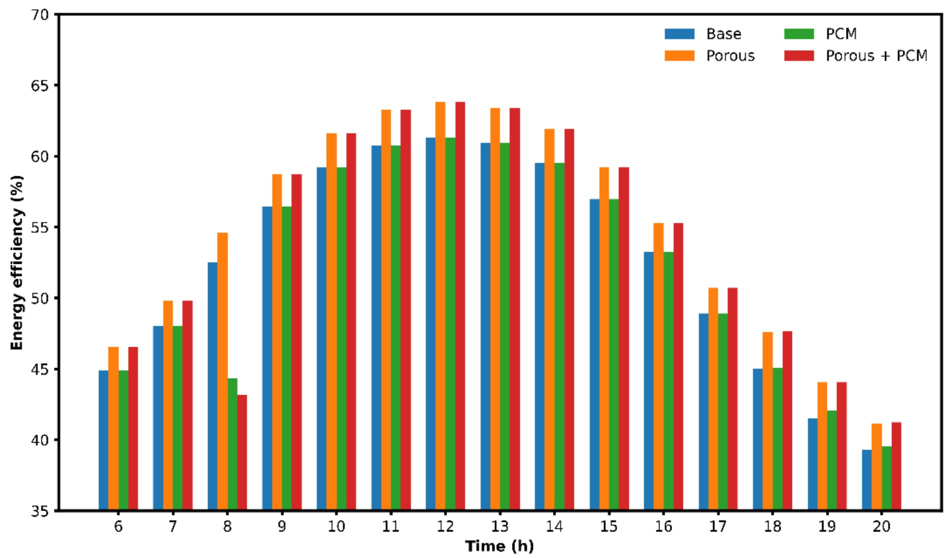

Figure 5: Instantaneous energy efficiency vs. operation time for Base, Porous, PCM, and Porous–PCM models.

The ultimate performance indicator, the cumulative daily freshwater yield, is illustrated in **Figure 6**, which presents the total distillate production for all four configurations throughout the operating period. The Base configuration produced a daily yield of 4.22 (L/m^2.day), whereas the Porous–PCM hybrid system achieved a substantially higher yield of 5.91 (L/m^2.day). This difference corresponds to a productivity improvement of 40% relative to the Base design. The contribution of the PCM is particularly evident during the late hours of operation, between 16:00 and 19:00, when the hybrid configuration sustains a notably stable production rate due to the continuous release of latent heat. This behavior confirms the effectiveness of the integrated thermal-management strategy in maintaining elevated evaporation rates and supporting long-duration productivity.

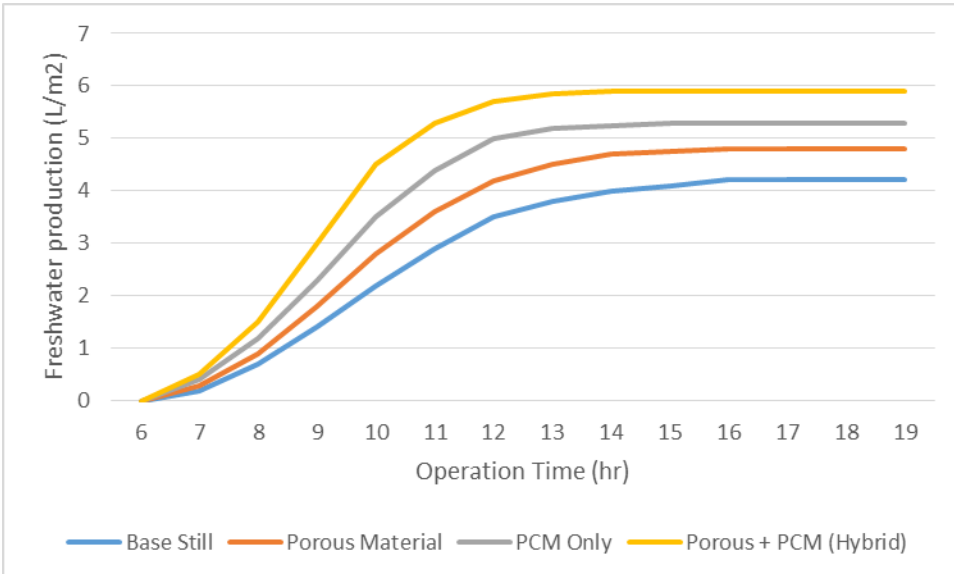

Figure 6: Daily freshwater productivity comparison for the Base, Porous, PCM, and Porous + PCM solar stills. The Porous-PCM hybrid model achieves the highest yield (e.g., 5.91 L/m2·day), confirming the synergistic effect of enhanced evaporative surface area and latent heat storage.

3.3. Exergy Analysis

A comprehensive exergy analysis was conducted to evaluate internal irreversibilities and the degradation of energy quality. The total exergy inflow from solar irradiation was partitioned into useful evaporative exergy and exergy destruction across multiple system interfaces. As illustrated in **Figure 7**, the Porous–PCM configuration exhibits the lowest destruction levels within the water and glass regions, showing a reduction of nearly 15% compared to the Base unit. The time-dependent trend of exergy efficiency, presented in **Figure 8**, indicates that the Porous–PCM still achieved a maximum efficiency of 27.8% at noon, whereas the Base configuration reached 18.4%. On a daily-average basis, the exergy efficiencies were 5.81%, 5.42%, 5.12%, and 4.66% for the Porous–PCM, PCM, Porous, and Base systems, respectively. The improvement of 1.15% in comparison with the Base design reflects more effective recovery of high-grade energy and reduced entropy generation, aligning with findings reported by Beik et al. [1] and El-Sebaii et al. [20].

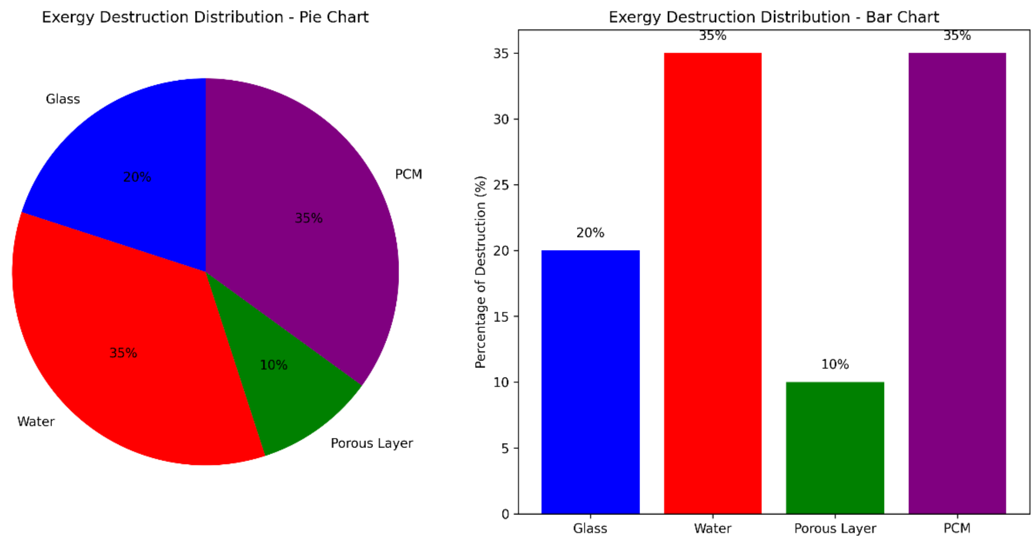

Figure 7: Exergy destruction distribution across components (glass, water, porous layer, PCM).

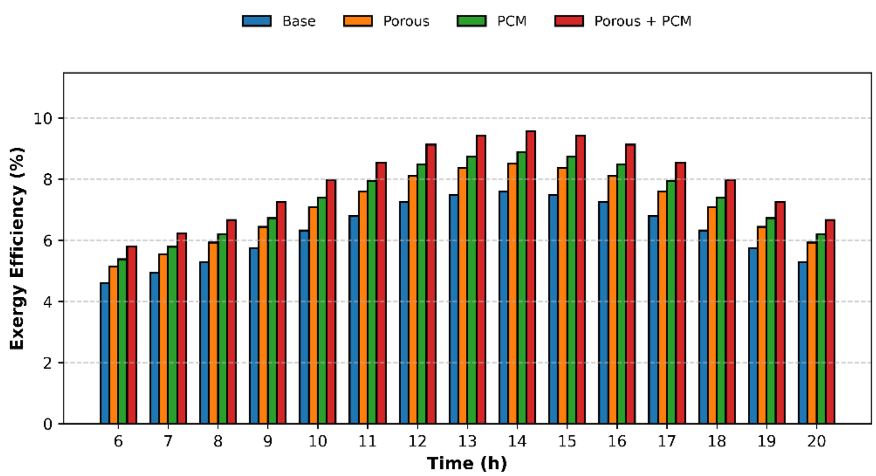

Figure 8: Instantaneous exergy efficiency vs. operation time for Base, Porous, PCM, and Porous–PCM models.

3.4. Exergoeconomic Performance

A comparative trend among the four studied configurations—Base, Porous, PCM, and the Porous–PCM hybrid—is illustrated in **Figures 9 and 10**, integrating exergy and economic indicators to clarify their relative behavior under varying levels of solar irradiance. As depicted in **Figure 9**, the cost rate of exergy destruction decreases consistently as solar intensity increases across all configurations, although the magnitude and rate of decline vary considerably. The Base system exhibits the highest destruction cost, beginning near 0.017 ($/L) at a solar intensity of 300 watts per square meter and decreasing to roughly 0.015 ($/L) at 1000 ($W/m^2$), indicating substantial irreversibility and poor thermodynamic performance. The Porous configuration achieves a lower destruction cost, decreasing from approximately 0.015 to 0.014 ($/L) due to improved capillary heat distribution, whereas the PCM-assisted design further reduces this value from about 0.014 to 0.0135 ($/L) as a result of basin-temperature stabilization provided by latent-heat buffering.

The Porous–PCM hybrid system surpasses all other configurations by maintaining the lowest exergy destruction cost, reaching nearly 0.013 ($/L) at high irradiance. The continuously declining trajectory with minimal curvature confirms the strong synergistic interaction between enhanced thermal conduction in the porous layer and the temperature-regulation capacity of the PCM. When compared with the Base configuration, the hybrid design achieves a cost reduction exceeding 25%, establishing its clear dominance in exergoeconomic efficiency across the solar-irradiance conditions characteristic of Kabul's climate.

A similar hierarchical pattern is evident in **Figure 10**, where the payback period decreases as the yield enhancement increases for all evaluated configurations. At zero yield improvement, the Base system shows the longest payback duration of 270 days. Incorporating a Porous layer shortens this period to 240 days, while the PCM design further reduces it to 215 days. The Porous–PCM hybrid system achieves the most favorable performance, lowering the payback time to only 185 days under a 25% yield increase.

The steepest decline observed in the hybrid-system curve signifies its superior economic viability and accelerated return on investment. The simultaneous reduction in the exergy-destruction cost rate (**Figure 9**) and payback duration (**Figure 10**) conclusively demonstrates the hybrid configuration's thermoeconomic superiority, characterized by the minimum cost of approximately 0.013 ($/L), the highest exergy utilization, and the most effective harnessing of available solar energy.

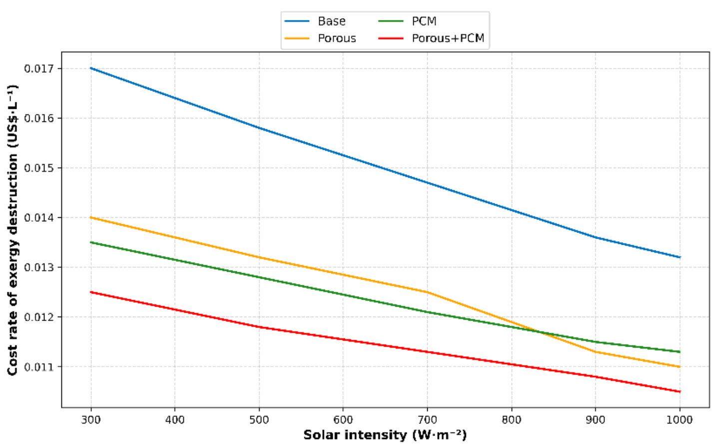

Figure 9: Cost rate of exergy destruction vs. solar intensity for all cases.

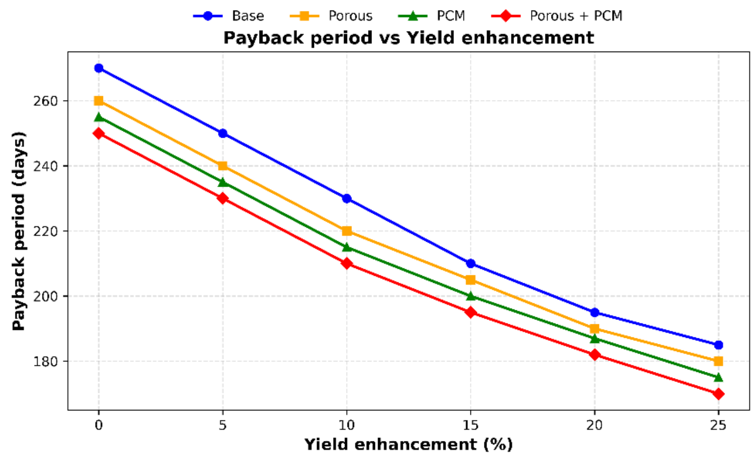

Figure 10: Payback vs. yield enhancement across configurations.

To complete the economic assessment, the specific cost of distilled water for all configurations was evaluated using the Specific Exergy Costing (SPECO) method, as shown in **Figure 11**. The initial investment and annualized expenses were normalized by the corresponding daily water production to determine the final product cost. The Base configuration exhibited the highest specific cost, reaching 0.019 ($/L). In line with the trends observed for both the exergy-destruction rate and the payback period, the Porous–PCM hybrid system produced the lowest specific water cost, calculated at 0.013 ($/L). This reduction of approximately 31.6% relative to the Base system provides strong evidence of its integrated thermoeconomic superiority and identifies it as the most economically viable option among all evaluated configurations.

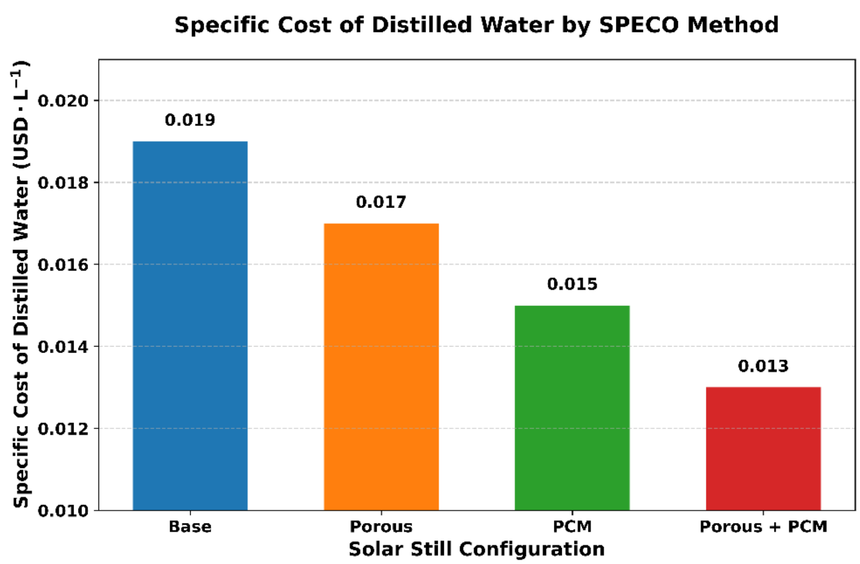

Figure 11: Specific cost of distilled water across different solar still configurations, determined by the SPECO method.

To ensure the robustness of the developed thermodynamic framework, an uncertainty analysis was conducted for the main operational parameters that could influence both energy and exergy efficiencies. Key input variables such as solar irradiance, basin temperature, and PCM melting point were individually perturbed by ±5 % to quantify their impact on thermal and exergetic outputs. The summarized results in **Table 3** indicate that variations in the main parameters lead to less than 4 % change in daily energy and exergy efficiencies, confirming the numerical stability and reliability of the model.

Table 3. Uncertainty propagation of major parameters for ±5 % variation.

Parameter	Base Value	±5 % Variation	Impact on η_{en} (%)	Impact on η_{ex} (%)
Solar intensity (W/m²)	1000	±50	±2.4	±1.8
Basin temperature (°C)	72	±3.6	±3.1	±2.7
PCM melting point (°C)	58	±2.9	±1.5	±1.2

3.5. Environmental Evaluation

The environmental assessment was undertaken using both direct CO_2-mitigation metrics and the Eco-indicator 99 methodology. As seen in **Figure 12**, the avoided CO_2 emissions were calculated using:

$$CO_{2,avoided} = E_{saved} \times EF_{grid}$$

Where $EF_{grid} = 0.85_{kg} CO_2 kWh^{-1}$. Furthermore, the normalized carbon-saving potential was evaluated relative to the thermal energy output of the system. The avoided CO_2 emission per unit electrical equivalent was estimated as:

$$CO_{2avoided,norm} = CO_{2avoided} E_{saved} = EF_{grid} = 0.85(kgCO_2kWh)^{-1}$$

Based on the daily energy yield of the hybrid Porous-PCM still ($3.6kWh\, m^{-2} day^{-1}$), the system prevented approximately $3.06\ kg\ CO_2$ per kWh of recovered solar energy. The economic valuation of this mitigation was determined using the cost of CO_2 reduction ($USD/kgCO_{2avoided}$) :

$$C_{CO_2} = C_F CO_{2avoided}$$

Yielding $0.0044 USD\ kg^{-1} CO_2$ avoided for the Porous-PCM configuration, which indicates a highly cost-efficient route toward carbon-neutral desalination compared with electricity-based units ($typically$ $0.010 - 0.015\ USDkg^{-1}CO_{2avoided}$ [7,13]) .

The Porous–PCM configuration achieved approximately $3.0kgCO_2m^{-2}day^{-1}$, representing a 52 % emission reduction compared to the Base still. Environmental load indices are summarized in **Figure 13**. The Eco-indicator decreased from $0.52\ Pt\ L^{-1}$ (Base) to $0.35\ Pt\ L^{-1}$ (Porous–PCM), highlighting the lower embodied-energy impact by substituting electricity-driven desalination with passive solar mechanisms and natural wool insulation. Related patterns were similarly observed by Elamy et al. [7] for hybrid solar desalination systems.

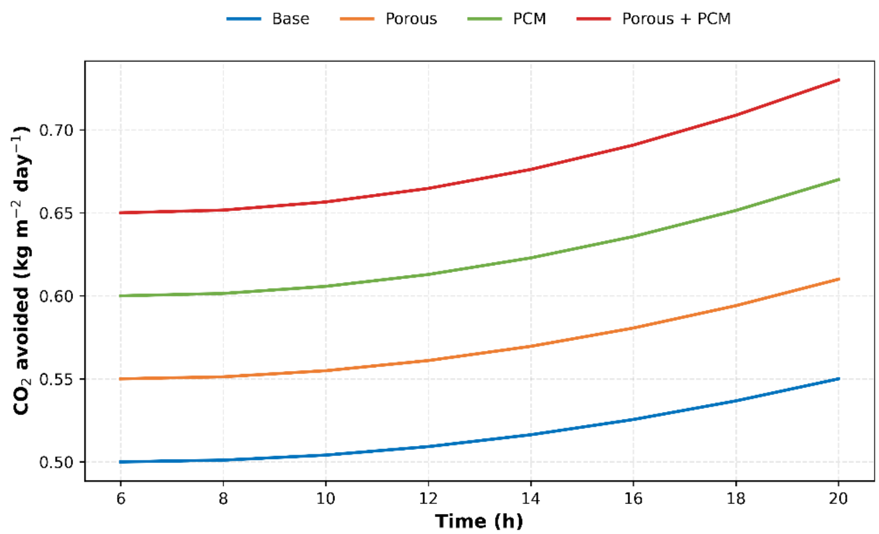

Figure 12: Daily CO_2 avoidance per m² collector area .

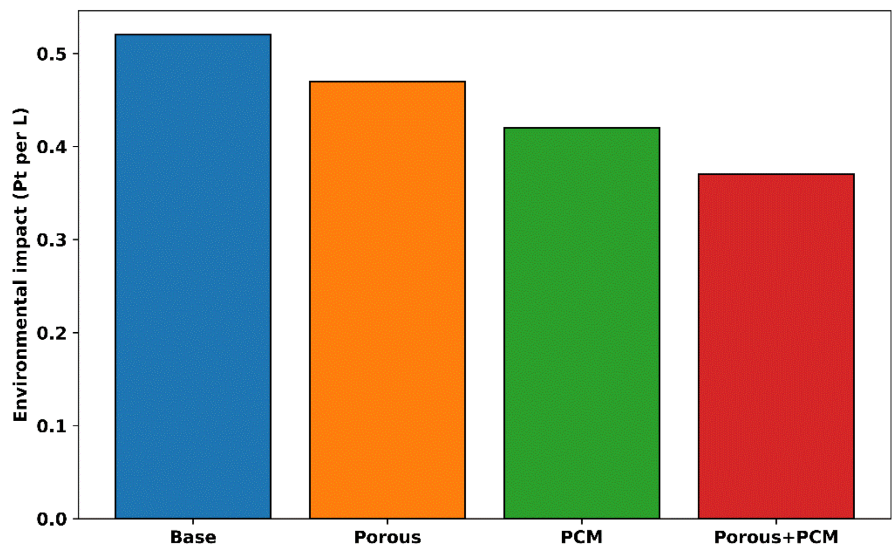

Figure 13: Eco-indicator 99 index per liter of water produced.

3.6. Integrated 4E Interpretation

The integrated outcomes across all 4E dimensions emphasize the synergistic benefits of coupling porous and PCM layers, as comprehensively summarized in **Table 4** and **Figure 14**. The data clearly demonstrates the superiority of the combined configuration, which achieved the highest thermal and exergetic efficiencies, alongside the lowest cost and highest carbon avoidance.

The simultaneous integration of the porous layer and the PCM significantly enhanced the system's thermodynamic performance. The mean daily energy efficiency increased to 83.52%, representing a notable gain of 14.98% relative to the Base configuration, which achieved 68.54%. In parallel, the exergy efficiency rose to 5.81% for the integrated system, reflecting an absolute improvement of 1.15% when compared with the Base value of 4.66%.

From an exergoeconomic perspective, the Porous–PCM configuration substantially lowered the cost of freshwater production, achieving a specific cost of 0.013 ($/L). This value corresponds to a 31.6% reduction relative to the Base system, which produced distilled water at 0.019 ($/L), thereby demonstrating the clear economic viability of the integrated design. Furthermore, the environmental assessment confirms the superior sustainability of the hybrid configuration, as it achieved a carbon-dioxide avoidance level of 3.00 (kg/m^2.day), compared with 1.98 (kg/m^2.day) for the Base case. This improvement, equal to a 52% increase in avoided emissions, underscores the strong environmental advantage offered by the coupled porous and PCM layers. Collectively, these outcomes validate the unified 4E framework and provide compelling evidence that integrating porous media with latent-heat storage mechanisms markedly elevates the overall performance and sustainability of solar still systems.

Table 4. Integrated 4E results: Comparative analysis of all studied solar still configurations.

Parameter	Base	Porous	PCM	Porous + PCM	Gain over Base
Energy efficiency (%)	68.54	71.73	80.31	83.52	+ 14.98
Exergy efficiency (%)	4.66	5.12	5.42	5.81	+ 1.15
Cost ($/L)	0.019	0.017	0.015	0.013	− 31.6 %
CO_2 avoidance (kg/m².day)	1.98	2.15	2.64	3.00	+ 52 %

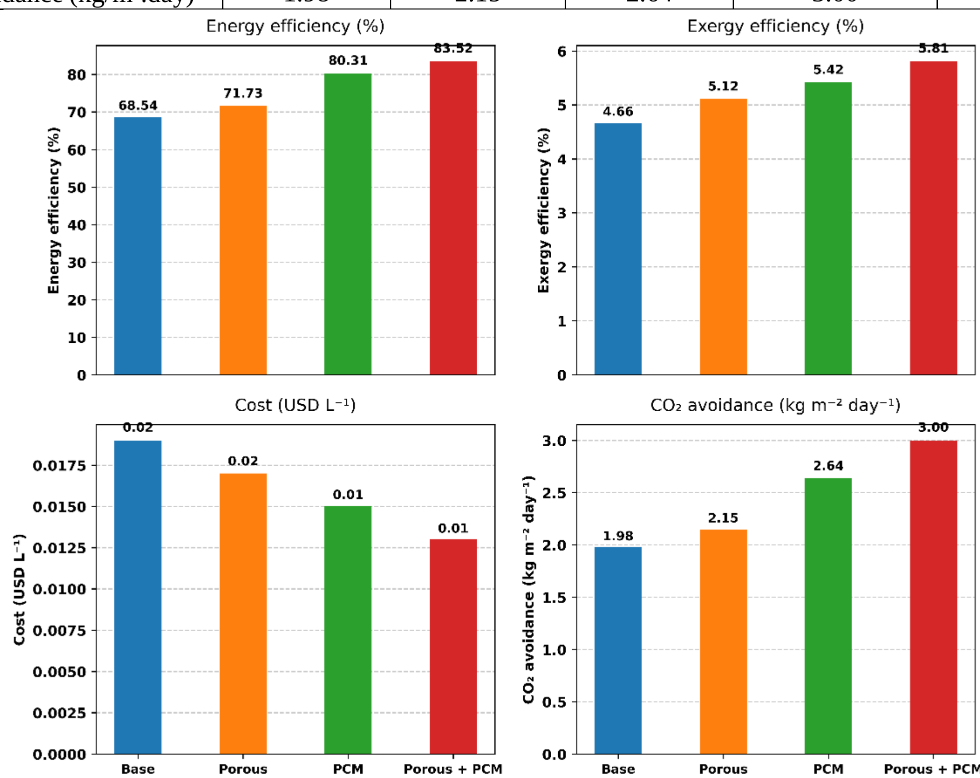

Figure 14: Integrated 4E Bar Comparison of Solar Still Configurations.

4. Conclusion

A comprehensive experimental–numerical investigation was conducted to evaluate the energy, exergy, exergoeconomic, and environmental performance of a hybrid Porous–PCM flat-plate solar still operating under the semi-arid climate of Kabul. Four configurations—Base, Porous, PCM, and the Porous–PCM hybrid—were comparatively assessed within the unified 4E framework.

The results demonstrated substantial improvements in productivity and sustainability arising from the synergistic interaction between the porous layer and the PCM. The daily freshwater yield increased from 4.22 (L/m^2) in the Base unit to 5.91 (L/m^2) in the hybrid configuration, reflecting an enhancement of roughly 40%. Thermal stabilization provided by the PCM reduced basin-temperature fluctuations, while the porous medium promoted uniform water-film evaporation through capillary rewetting. As a result, the hybrid system maintained peak basin temperatures of about 72 ^{0}C and sustained elevated evaporation rates well into the post-sunset hours.

From an energy perspective, the mean daily energy efficiency rose from 68.54% for the Base configuration to 83.52% for the hybrid design. The exergy analysis further indicated that the Porous–PCM system achieved an exergy efficiency of 5.81%, representing an absolute increase of 1.15% and a relative improvement of 47% compared with the Base model. The distribution of exergy destruction revealed notable reductions in irreversibilities within both the water and glass interfaces, confirming the strong coupling effect between the porous layer and the latent-heat storage system.

The exergoeconomic evaluation using the SPECO method showed a 32% reduction in the cost of distilled water, decreasing from 0.019 ($/L) in the Base configuration to 0.013 ($/L) for the Porous–PCM still. The payback period similarly improved, falling to nearly 185 days under Kabul's average solar-irradiance conditions, thereby demonstrating excellent techno-economic viability.

Environmental indicators reinforced the sustainability advantage of the hybrid configuration. The daily carbon-dioxide avoidance reached 3.00 (kg/m^2), compared with 1.98 (kg/m^2) for the Base system, yielding a 52% improvement in emission reduction. In addition, the Eco-indicator 99 value decreased from 0.52 (Pt/L) in the Base case to 0.35 (Pt/L) in the hybrid configuration, indicating reduced embodied energy and a smaller ecological footprint.

Collectively, these findings confirm that the Porous–PCM solar still designed under the unified 4E framework exhibits superior performance across all energy, exergy, exergoeconomic, and environmental dimensions. The integrated use of capillary-driven porous media and latent-heat storage enables dynamic thermal buffering that enhances hourly evaporation and nighttime condensation, establishing the system as a highly promising solution for sustainable desalination in regions with medium-to-high solar potential.

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Declaration of Interest Statement

Article title: A Unified 4E Framework for Porous-PCM Integrated Solar Stills: Synergistic Enhancement of Energy, Exergy, Economic, and Environmental Performance

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