

# Optimal Design of Solar Desalination Systems for Arid Regions

**Abdullah Alghafis**

Associate Professor, Department of Mechanical Engineering  
College of Engineering, Qassim University, Saudi Arabia  
[a.alghafis@qu.edu.sa](mailto:a.alghafis@qu.edu.sa)

**Mohamed Nejlaoui**

Associate Professor, Department of Mechanical Engineering  
College of Engineering, Qassim University, Saudi Arabia  
[m.nejlaoui@qu.edu.sa](mailto:m.nejlaoui@qu.edu.sa)

## Abstract

The escalating global freshwater insufficiency, propelled by rapid population growth, necessitates a sophisticated approach to system design that harmonizes technical performance with economic viability. Although desalination provides a critical alternative to traditional water supplies, the design of small-scale renewable systems frequently relies on single-objective or purely performance-based metrics, which often restricts their real-world implementation. To address this, the current study redefines the design of a solar still desalination system integrated with a solar collector (SS-SC) as a multi-objective decision problem, viewed through the lens of industrial engineering and operations management. By utilizing a MATLAB-based numerical model to evaluate thermal efficiency and total system expenditure under realistic constraints, the design challenge is resolved via a Multi-Objective Imperialist Competitive Algorithm (MICA). This process generates a Pareto-optimal solution set that explicitly delineates the trade-offs between cost and efficiency, offering stakeholders a structured decision space to select configurations tailored to specific budgetary and operational needs rather than a singular, rigid result. Benchmarking these optimized SS-SC configurations against existing literature reveals significant advancements in both performance and economic indicators, ultimately underscoring the vital role of multi-objective decision analysis in facilitating the cost-effective and scalable deployment of solar desalination technologies.

## Keywords

Solar desalination, Optimization, Low-cost, Sustainability, Renewable energy.

## 1. Introduction

The intensifying worldwide crisis of potable water shortages, fueled by rapid demographic expansion and the finite nature of reachable surface water, has positioned seawater desalination as a vital pillar for strategic water resource management (Shemer et al. 2023). Within the diverse landscape of desalination methods, solar-powered techniques are gaining significant traction for their ability to promote environmental sustainability and decrease reliance on carbon-intensive energy (Al-Addous et al. 2024). Solar still configurations are among the most straightforward and reachable solar-driven technologies; they provide a low-tech, decentralized solution by leveraging solar radiation to vaporize brine and capture distilled water via condensation (Younis et al.2022).

Nevertheless, the real-world implementation of these systems is frequently hampered by the tension between thermal productivity and financial viability. As a result, current academic focus has moved toward assessing structural optimizations and multi-source setups (such as the incorporation of secondary solar thermal collectors) to boost output

without compromising affordability (Yin et al. 2024). From an engineering and operational standpoint, these hurdles emphasize the importance of developing structured methodologies that deliberately weigh technical enhancements against budgetary limitations, moving beyond a narrow focus on purely thermodynamic efficiency.

Extensive academic inquiry has previously scrutinized the economic viability and thermodynamic efficiency of both independent solar stills and multifaceted desalination frameworks (Selimefendigil et al. 2022). Researchers have specifically investigated a diverse array of structural variables, such as the physical configuration of the still, the selection of glazing and insulation types, and the addition of thermal storage media designed to accelerate evaporation (Indrani et al.2025). Moreover, combining desalination modules with external thermal harvesters, like flat plate solar collectors, has been studied to establish a more stable and elevated thermal baseline, which can significantly boost the output of potable water (Muftah et al. 2025, Babaebazaz et al. 2021). These studies have utilized a combination of empirical testing and computational simulations to evaluate operational success across varying environments, frequently underscoring the inherent friction between maximizing thermal yield, managing capital expenditures, and reducing technical sophistication (Najlaoui et al. 2025, Kumar et al. 2022, Prakash et al. 2022, Abu-Zeid et al. 2024). To enhance the efficiency of solar-driven desalination frameworks, the application of multi-objective optimization strategies has surfaced as a robust method for managing diverging goals, such as maximizing thermodynamic output while curtailing both initial capital and ongoing maintenance costs (Zhang et al. 2024, Wang et al.2023, Bade et al. 2025). These mathematical techniques facilitate the discovery of Pareto-optimal configurations, providing engineers with a selection of design alternatives that embody the most effective compromises between competing criteria (Gevorkov et al. 2025, Agha Kassab et al. 2024).

In the context of multi-objective algorithms utilized for solar water purification, the Modified Imperialist Competitive Algorithm (MICA) offers a persuasive methodology, characterized by distinctive exploration and refinement phases modeled after socio-political developmental patterns (Bilel et al. 2019). The primary motivation for adopting MICA in this study is its capacity to successfully traverse the intricate, multi-peaked search landscapes typical of desalination system architecture. Through its specific mechanics of imperialist rivalry and assimilation, MICA provides a comprehensive global search range, which helps prevent the algorithm from stalling at suboptimal local points, a common drawback in alternative optimization methods.

Additionally, its straightforward execution and minimal requirement for control parameter tuning, relative to other evolutionary methods, make it a favorable choice for resolving complex engineering bottlenecks (Nejlaoui et al. 2022, Nejlaoui et al. 2021, Najlaoui et al. 2023). By utilizing MICA, this research can pinpoint ideal designs for the DS-FP system that achieve a more refined equilibrium between thermal yield and financial economy than traditional heuristic methods, thereby offering meaningful advancements to the domain of affordable solar desalination.

## **2. System Modelling and Methodology**

### **2.1 Spatial Context and Climatic Profile of the Qassim Province**

Situated in central Saudi Arabia's arid Najd region, Unaizah (Qassim) is characterized by severe freshwater scarcity and a hot desert climate. The area sits south of Wadi Al-Rummah, surrounded by expansive sand formations that intensify its dry environment. However, from a renewable energy standpoint, the region's exceptionally high annual solar irradiance positions it as an ideal location for solar-based applications. This combination of high solar potential and urgent water demand makes Unaizah a strategic case study for evaluating the viability of sustainable, cost-effective desalination systems (Table 1).

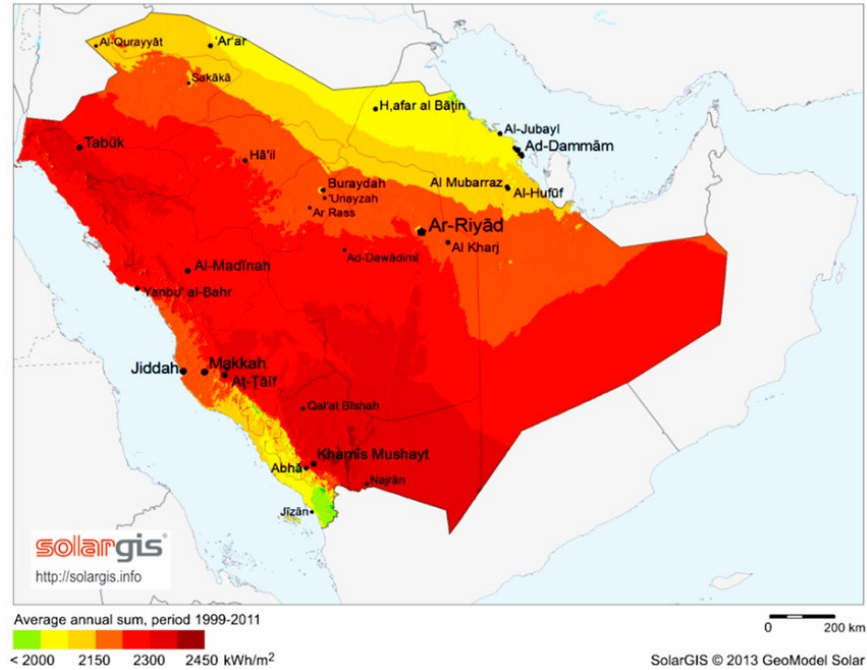


Figure 1. Site location and annual solar resource assessment for the Unaizah district (Alotaibi et al.2018, AlSharabi et al. 2025)

## 2.2 The SS-SC System

The integrated solar still and flat-plate collector (SS-SC) operates as an active desalination framework that significantly boosts freshwater yields by merging the straightforward design of a traditional solar still with the superior energy harvesting capabilities of an external thermal collector. This dual-stage process begins with solar energy collection, where a flat-plate collector utilizes a dark absorber plate and a greenhouse-effect glass cover to capture solar radiation, heating a fluid medium circulated through specialized tubing (Figure 2.a). This thermally enriched fluid is then directed into the basin of the solar still, where it serves as a concentrated heat source that elevates the temperature of the saline water much more rapidly than passive systems relying on direct sunlight alone. As this intensified heat triggers a surge in evaporation rates, the resulting water vapor ascends to meet the cooler transparent glazing of the still, condensing into high-purity freshwater that is channeled into storage while brine and impurities remain isolated in the basin (Figure 2.b).

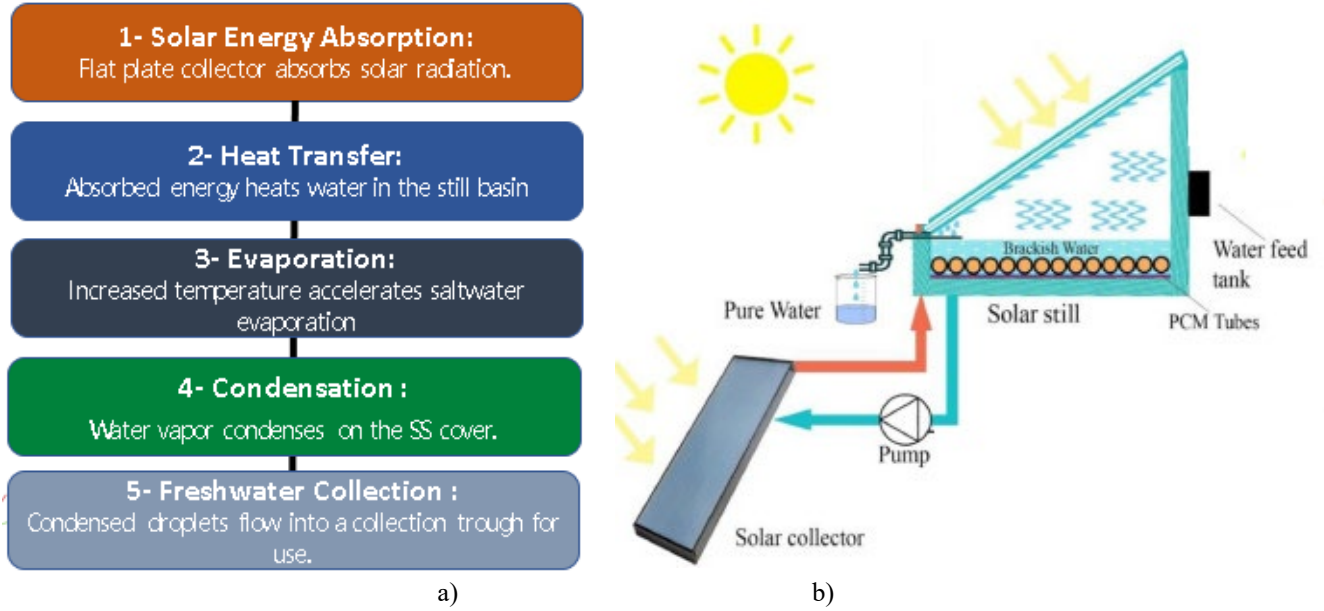


Figure 2. SS-SC operational and structure

### 2.3. SS-SC Thermal Analysis

The transient thermal behavior of the integrated SS-FPC system is governed by a series of energy balance equations across the glass cover, basin, water mass, and collector (Sivakumar et al. 2024).

#### 2.3.1 Glass Cover and Basin Liner

The thermal interaction at the glass cover accounts for solar absorption, internal exchange with the water surface, and external losses to the ambient air ( $T_a$ ). The inner ( $T_{gi}$ ) and outer ( $T_{go}$ ) glass temperatures are derived by balancing convective ( $h_c$ ), radiative ( $h_r$ ), and evaporative ( $h_e$ ) heat transfer coefficients.

Similarly, the energy balance for the basin liner ( $T_b$ ) integrates the fraction of solar energy absorbed by the liner ( $\alpha_b$ ) and the water ( $\alpha_w$ ), while considering total heat loss to the ambient ( $U_b$ ) through insulation of thickness  $L_i$  and conductivity  $K_i$ .

#### 2.3.2 Integrated Water Mass and SC System

The core of the active system is the water mass ( $M_w$ ) energy balance. By incorporating the useful energy gain ( $Q_u$ ) from the Solar Collector (SC), the governing differential equation is expressed as:

$$\frac{dT_w}{dt} + \alpha T_w = f(t) \quad (1)$$

Where:

- $\alpha$ : Represents the overall heat loss factor to the ambient environment.
- $f(t)$ : Accounts for the combined solar gain from the still and the integrated SC.

The useful energy  $Q_u$  from the  $N$  collectors is determined by the heat removal factor ( $F_R$ ) and the collector efficiency factor ( $F'$ ), defined as:

$$Q_u = N A_c F_R [(\alpha \tau)_c I_c(t) - U_L (T_w - T_a)] \quad (2)$$

#### 2.3.3 System Performance Metrics

The hourly freshwater yield ( $m_{ew}$ ) is calculated based on the evaporative heat transfer and the latent heat of vaporization ( $L$ ):

$$m_{ew} = \frac{h_{ew}(T_w - T_{gi})}{L} \times 3600 \quad (3)$$

The overall thermal efficiency of the SS-SC system is then determined by the ratio of the cumulative latent heat of the total daily yield ( $M_{ew}$ ) to the total solar energy incident on both the still ( $A_s$ ) and the collector ( $A_c$ ):

$$\eta_{th} = \frac{\sum m_{ew} \cdot L}{\sum [I_s(t)A_s + I_c(t)A_c] \cdot \Delta t} \quad (4)$$

### 3.3 Total Cost of the desalination system

The SS-SC total cost, including investment and operating costs, is the subject of the economic analysis. The investment cost ( $INV_{cost}$ ) includes the capital costs of different components of SS-FPC ( $SS-FPC_{cost}$ ) and the pump ( $PUM_{cost}$ ):

$$INV_{cost} = SS-FPC_{cost} + PUM_{cost} \quad (5)$$

$$INV_{cost} = \phi \left\{ \alpha_1 (P_a)^{\beta_1} + \alpha_2 (T_e)^{\beta_2} + \alpha_3 (V_{insu})^{\beta_3} + \alpha_4 (A_{co})^{\beta_4} + \alpha_5 (P_{pump})^{\beta_5} \right\} \quad (6)$$

$\phi$  indicates the collector's assembly factor,  $V_{insu}$  is the volume of the insulator.  $P_a$ ,  $T_e$  and  $A_{co}$  are the absorber panel, the external tube and the cover's surfaces, respectively.

$\alpha_{1-5}$  and  $\beta_{1-5}$  depict the chosen coefficients based on the obtainable market prices of the equipment.

The required power for the pump ( $P_{pump}$ ) is given by:

$$P_{pump} = \frac{m\Delta P}{\eta_p \rho} \quad (7)$$

$\eta_p$ ,  $\rho$  and  $\Delta P$  denote, respectively, efficiency of the pump, density of the fluid, and fall in pressure.

The cost of operation ( $OPE_{cost}$ ) depends on the electric cost per unit ( $P_{el}$ ), annual pump hours ( $P_h$ ), and required pump pressure ( $P_{pump}$ ).

$$OPE_{cost} = P_{el} P_h P_{pump} \quad (8)$$

The SS-FPC total cost, based on equations (6) and (8), is calculated as:

$$TotalCost = \xi INV_{cost} + OPE_{cost} \quad (9)$$

$\xi$  represents the yearly cost factor, as indicated by:

$$\xi = \frac{1}{1 - (1+i)^{-y}} \quad (10)$$

$i$  and  $y$  represent the annual interest rate and the system lifetime.

The second objective function to be considered is the minimization of SS-FPC total cost.

## 4. Multi-Objective Optimization Methodology

### 4.1 The optimization problem formulation

To assess the coupled thermal and financial feasibility of the DS-FP framework, the system's efficiency and cumulative costs (derived from Equations 4 and 9) were analysed through a multi-objective lens using a specific suite of Decision Variables (DVs).

By employing the MICA approach, we aim to find the DVs that concurrently lead to the highest SS-SC efficiency and the lowest total cost. This multi-faceted optimization challenge for the DS-FP can be expressed as:

$$\left\{ \begin{array}{l} \text{Maximize Efficiency} \\ \text{Minimize total Cost} \\ \text{By considering the DVs ranges} \end{array} \right. \quad (11)$$

The operational boundaries and parametric ranges for these variables are summarized in Table 1, while additional static parameters are maintained in accordance with established literature (AlSaleem et al. 2022, Nejlaoui et al. 2026).

Table 1. Ranges of DVs.

$A_c$	Absorber Panel Surface Area	0.1 – 0.5	$m^2$
$M_w$	Water Mass in Basin	20 – 60	$kg$
$\dot{m}$	Fluid Mass Flow Rate	0.003 – 0.035	$kg/s$
$L_i$	Insulation Material Thickness	0.001 – 0.01	$m$
$L_g$	Glass Cover Thickness	0.003 – 0.006	$m$

#### 4.2 The MICA method

The Multi-Objective Imperialist Competitive Algorithm (MICA) simulates the geopolitical evolution of empires to resolve complex optimization trade-offs (Figure 3). The process initializes with a population of "countries," which are partitioned into "imperialists" (high-performing solutions) and "colonies" (subsidiary solutions) to establish distinct empires. Exploitation of the search space is achieved through "assimilation," where colonies are mathematically shifted toward their respective imperialist to refine promising data points. To maintain global search integrity and bypass local optima, a "revolution" mechanism is integrated, introducing stochastic variations that force the algorithm to explore uncharted regions. MICA manages conflicting goals by utilizing Pareto dominance to isolate non-dominated solutions, which are preserved in an external archive as the most effective trade-offs discovered. The refinement process culminates in "imperialistic competition," a dynamic phase where dominant empires absorb the colonies of failing ones. Empires that lose their entire colonial base are systematically dismantled, effectively narrowing the search focus toward the most mathematically robust regions of the solution space (Figure 3).

The cyclic sequence involving assimilation, stochastic revolution, Pareto dominance assessment, archive refinement, and imperialist rivalry persists until a specified stopping condition is satisfied. The algorithm ultimately yields a collection of non-dominated solutions preserved within the external archive, serving as a high-fidelity representation of the Pareto frontier for the multi-objective problem. This resulting dataset provides stakeholders with a spectrum of optimized design configurations, each illustrating a unique equilibrium between the conflicting performance and economic targets.

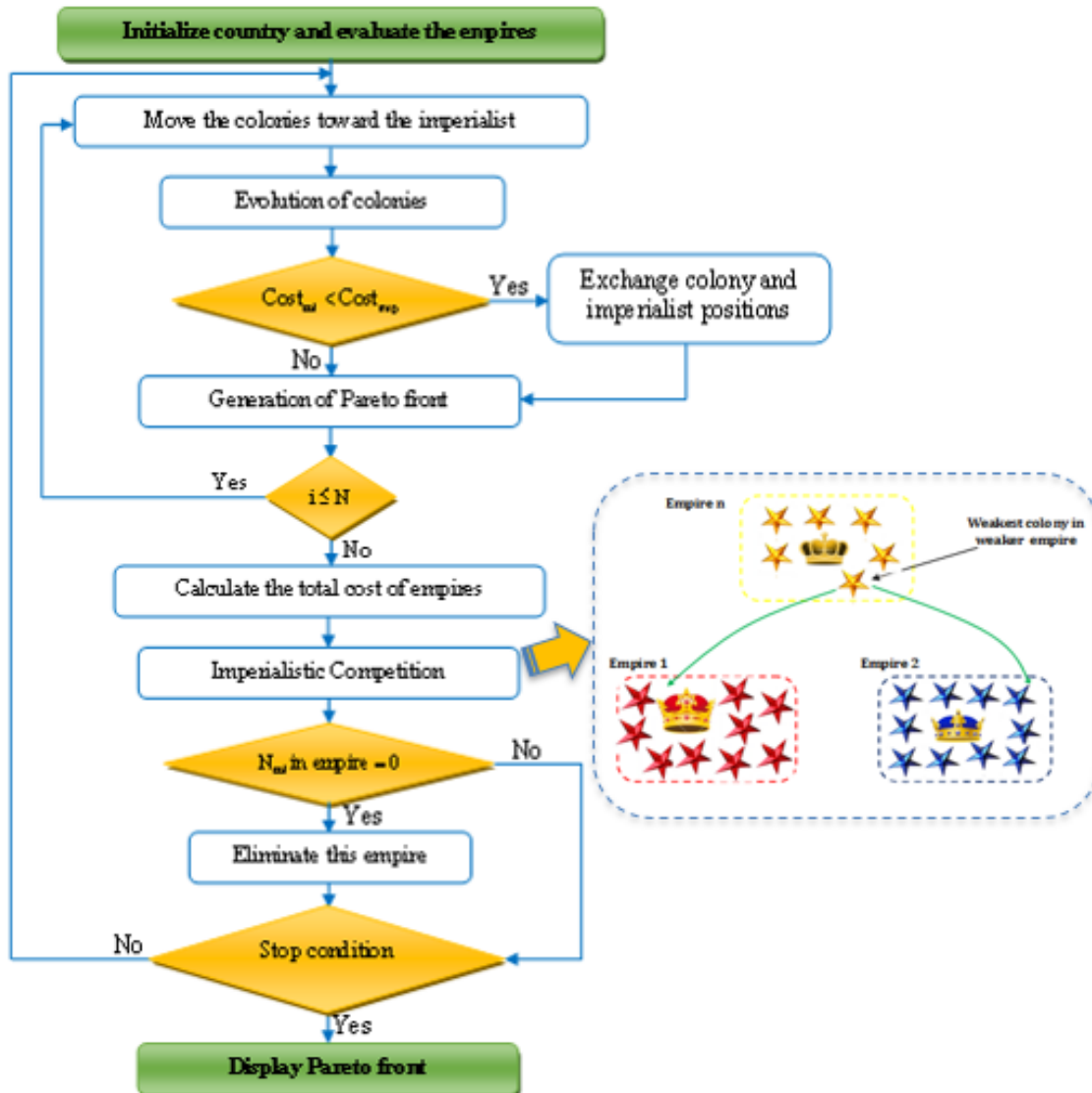


Figure 3. The MICA method (Bilel et al. 2019)

## 5. Results and Discussion

### 5.1 Optimal SS-SC results

In the context of SS-SC optimization, the Pareto optimal set defines a specialized boundary where any improvement in thermal efficiency inevitably necessitates a rise in capital expenditure, and conversely, any cost reduction results in a performance penalty (Fig. 4). This frontier of non-dominated solutions serves as a strategic map of the design space, illustrating the fundamental friction between maximizing solar energy harvesting and minimizing economic overhead. By navigating this spectrum, designers can identify a specific SS-SC configuration that aligns with localized project demands or strict budgetary constraints, recognizing that the peak of system performance is always governed by the law of diminishing economic returns (Figure 4).

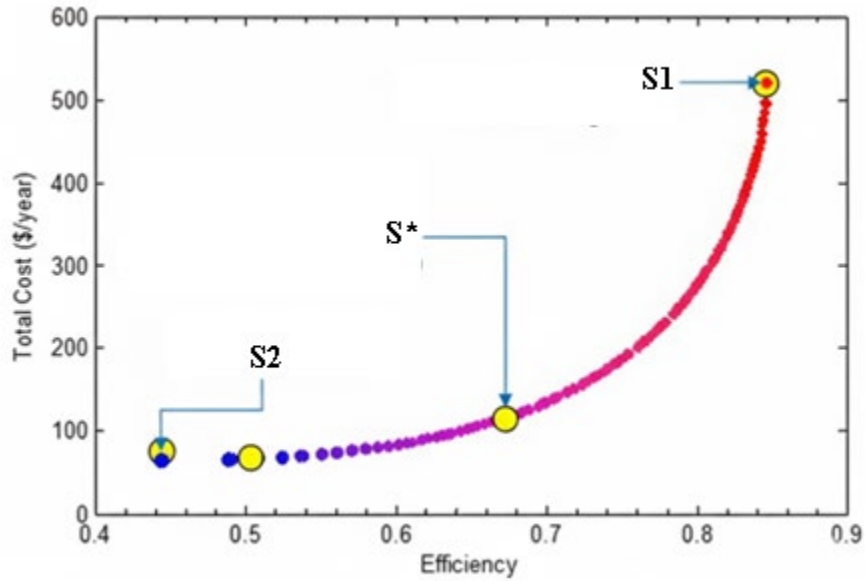


Figure 4. Pareto Optimal Solutions

The performance boundaries of the SS-FP system are delineated in Fig. 4 through three distinct benchmark configurations: S1, S2, and the prioritized optimal, S\*. The S1 variant serves as the thermodynamic ceiling, maximizing thermal efficiency at the expense of capital investment. In contrast, the S2 configuration represents the most aggressive cost-minimization strategy, sacrificing performance for economic accessibility. The multi-objective MICA framework identifies S\* as the superior compromise; with a calculated efficiency of 67.39% and a corresponding annual expenditure of 112.49 \$/year, it provides the most viable equilibrium for practical deployment, effectively reconciling the tension between operational output and financial constraints. A comprehensive breakdown of the design variables corresponding to the three benchmark configurations (S1, S2, and the optimal S\*) is presented in Figure 5.

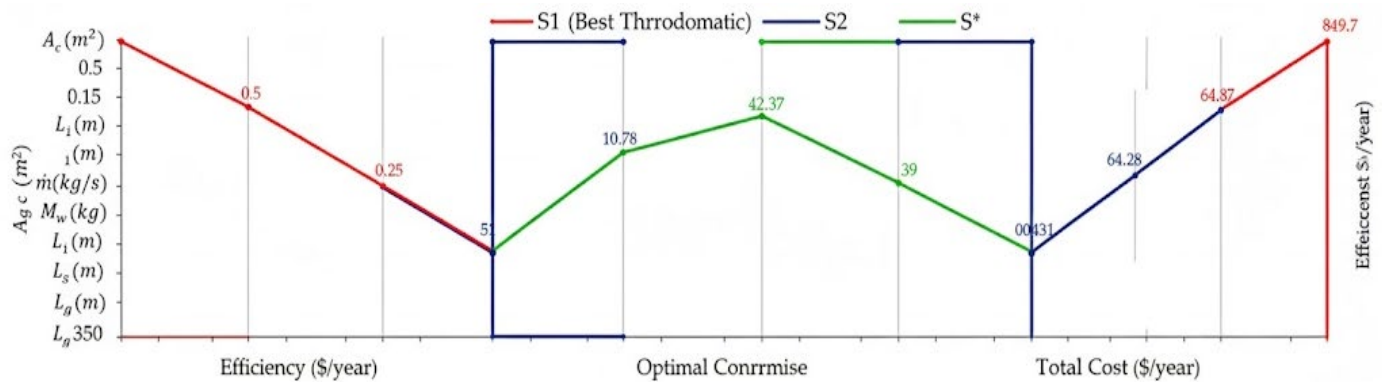


Figure 5. Parallel coordinates plot of design solutions

The annual thermal profile of the SS-SC system is depicted in Figure 6, which tracks the temperature fluctuations of the saline water ( $T_w$ ) and the inner glass cover ( $T_{gi}$ ). Both components demonstrate highly synchronized thermal behaviour throughout the seasonal cycle, with minimum temperatures occurring during early winter mornings and peak thermal performance recorded during the mid-summer months.

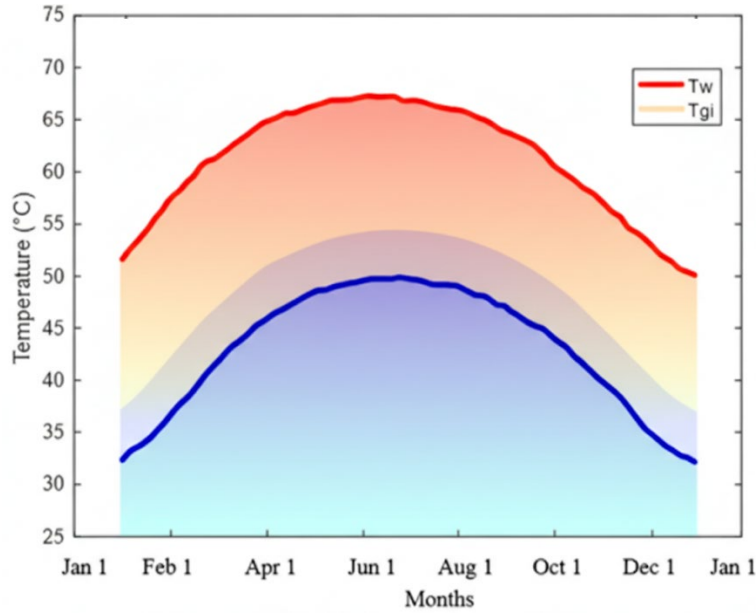


Figure 6. Maximum yearly Trend of Tw and Tgi at Noon

Thermal gradients within the system are clearly illustrated in Figure 6, where the inner glass cover maintains a consistently lower temperature profile relative to the saline water. Specifically, water temperatures fluctuate between approximately 60°C in the winter and 71°C during the summer peak. In contrast, inner glass temperatures range from a minimum of 30°C to a maximum of 50°C across the same period. To further examine system sensitivity to diurnal solar variations, Figure 7 provides the SS-SC efficiency profiles across representative days in May.

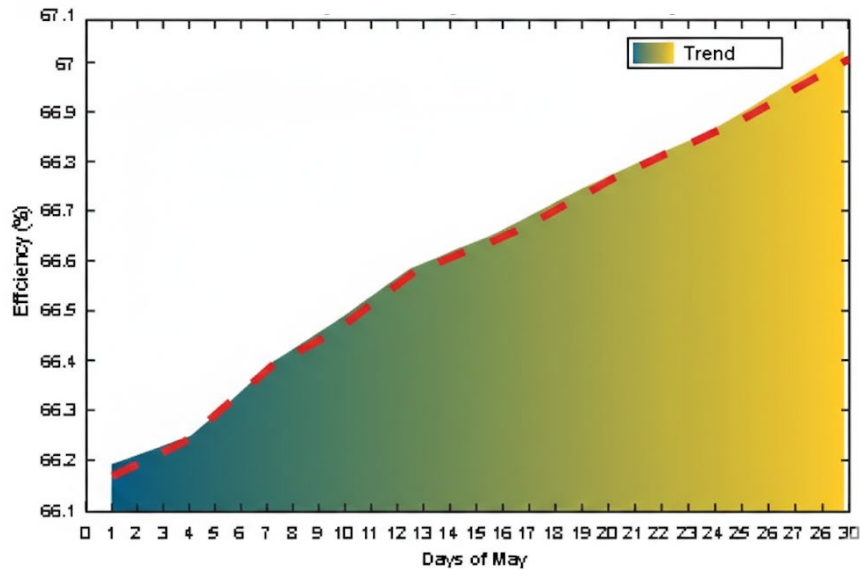


Figure 7. Maximum Daily Efficiency Changes of SS-FP in May 2024

As illustrated in Figure 7, the efficiency exhibits a quasi-linear upward trend throughout May, consistent with the seasonal rise in ambient temperatures and solar irradiance. To provide a high-resolution analysis of these thermal dynamics, Figure 8 presents the diurnal temperature variations for both the saline water and the inner glass cover specifically for the 11th of May, 2024.

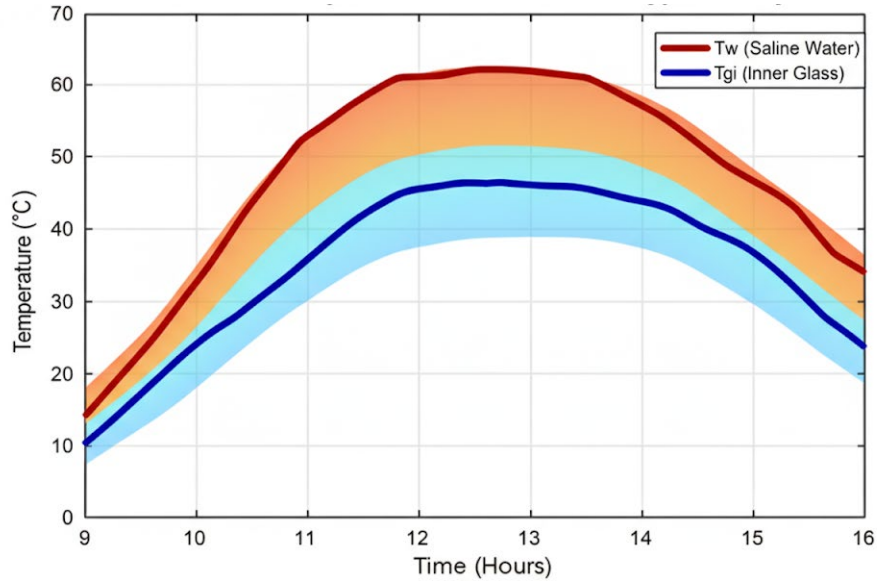


Figure 8. Tw and Tgi Temperature Trends for May 11, 2024

On May 11, 2024, both the saline water and the inner glass cover displayed synchronized thermal profiles, initiating at their daily minima around 9:00 AM before escalating to their respective peak temperatures at solar noon.

## 5.2 Comparison with literature

To validate the effectiveness of the proposed MICA-driven framework, the performance of the optimized double-slope flat-plate (SS-SC) system was benchmarked against established literature, including a single-objective efficiency-focused study (Abu-Zeid et al. 2024) and models that incorporated cost without employing optimization (Kumar et al. 2022, Prakash et al. 2022). These specific works serve as a pertinent basis for comparison as they represent typical design strategies; however, while (Abu-Zeid et al. 2024) prioritized efficiency regardless of cost and (Kumar et al. 2022, Prakash et al. 2022) considered expenses without pursuing an optimal balance, our research addresses the critical need for simultaneous optimization. Furthermore, unlike the rule-based methodologies in (Prakash et al. 2022, Abu-Zeid et al. 2024) that lack adaptability, our approach ensures inherent optimality, as evidenced by the data in Table 1, which reveals that our design achieves a substantial 31.33% improvement in efficiency compared to (Prakash et al. 2022) and a 49.78% reduction in total cost relative to (Kumar et al. 2022).

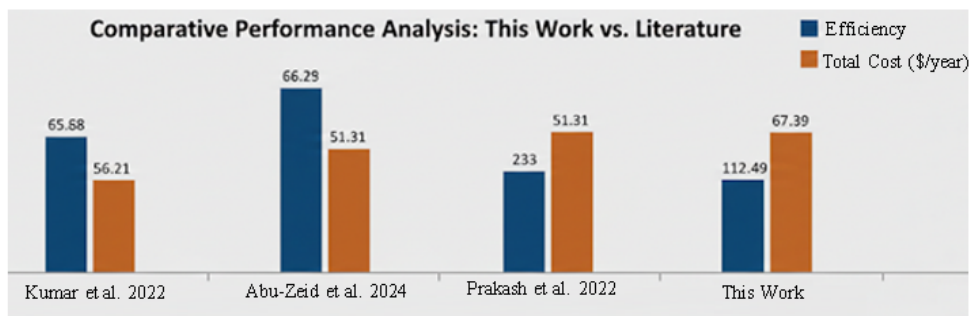


Figure 9. Comparative performance analysis

The superior performance of the optimized double-slope flat-plate (SS-SC) system stems directly from the implementation of the Multi-Objective Imperialist Competitive Algorithm (MICA). This sophisticated technique is specifically engineered to manage competing objectives, such as thermal efficiency and economic cost (Figure 9), simultaneously. By leveraging MICA's unique attraction-repulsion (AR) mechanism, the optimization process explores the Pareto front more thoroughly than traditional methods, identifying design configurations that achieve an ideal equilibrium between high performance and financial viability. Unlike the comparative studies in existing

literature, which often lack a unified framework to address these trade-offs, this MICA-driven approach ensures that the resulting designs are both reliable and optimized for real-world constraints.

These outcomes hold substantial weight when positioned against established research, which frequently prioritizes one metric at the expense of the other. By contrast, this multi-objective methodology uncovers solutions that provide superior efficiency without the typical disproportionate cost increases seen in previous designs. Achieving these gains (such as the 31.33% efficiency boost and 49.78% cost reduction) offers a more pragmatic and economically feasible pathway for solar energy technology. Ultimately, by delivering a compelling trade-off between performance and affordability, these optimized DS-FP systems are better positioned for widespread adoption, providing engineers and researchers with a refined set of design choices that contribute meaningfully to sustainable energy goals.

## **6. Conclusions**

This work addresses the critical issue of freshwater shortages by framing the design of a solar still integrated with a flat plate collector (SS-SC) as a dual-task of multi-objective optimization and decision support. By integrating a MATLAB-based numerical performance model with the Multi-Objective Imperialist Competitive Algorithm (MICA), the study systematically analyzes the fundamental trade-offs between thermal efficiency and total system expenditure, moving beyond the limitations of single-metric performance targets. This methodology facilitates the discovery of Pareto-optimal SS-SC configurations, empowering designers to make data-driven selections that balance operational excellence with real-world economic constraints.

Benchmarking against existing literature confirms that these optimized designs deliver consistent advancements in both efficiency and cost-effectiveness. Crucially, the results demonstrate that significant performance benchmarks can be reached at a fraction of the cost required by traditional designs, exposing the inefficiencies of the purely efficiency-driven or single-objective optimization methods prevalent in earlier studies. The resulting Pareto front offers a transparent decision-making environment, enabling stakeholders to customize system configurations based on specific budget ceilings, regional water requirements, and local deployment conditions.

From the standpoint of industrial engineering and operations management, the core contribution of this research is the transition of solar desalination design from a simple performance-focused exercise into a sophisticated, structured decision-making framework. This approach significantly boosts the commercial viability of solar desalination by advocating for cost-conscious, scalable, and context-specific engineering choices. These findings provide a strategic roadmap for deploying affordable solar desalination technologies (particularly in high-solar-irradiance regions with scarce water supplies) while establishing a robust foundation for future research into operational uncertainty, scalability, and full lifecycle analysis.

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## **Biographies**

**Dr. Abdullah Alghafis** earned his undergraduate degree in Mechanical Engineering from Qassim University in 2010. He subsequently completed in the U.S. for Master's degree at University of Dayton and PhD at Lehigh University in 2014 and 2019, respectively. Currently, he serves as an Associate Professor in the Department of Mechanical Engineering at the College of Engineering, Qassim University, Saudi Arabia. His primary research interests include Renewable Energy, Solar energy, biomass and optimization of renewable energy systems.

**Dr. Mohamed Nejlaoui** earned his undergraduate degree in Mechanical Engineering from the National Engineering School of Monastir (Tunisia) in 2005. He subsequently completed his Master's degree and PhD at the same institution in 2008 and 2013, respectively. Currently, he serves as an Associate Professor in the Department of Mechanical Engineering at the College of Engineering, Qassim University, Saudi Arabia. His primary research interests include robotics, mechatronics, control and optimization of renewable energy systems.