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Economic Analysis of a Tower-Shaped Hybrid Desalination Plant Integrating (HDH- PSD) Humidification-Dehumidification with Pyramidal Solar Distillation

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Abstract: Economic factors are the primary determinants of the selection and deployment of desalination technologies. This study provides an in-depth economic assessment of an innovative tower-configuration desalination facility that combines two synergistic technologies: humidification-dehumidification (HDH) processes and pyramidal solar still (PSS) systems. The economic evaluation utilized a comparative framework that examined three distinct operational scenarios: the integrated hybrid configuration alongside each technology functioning as a standalone system. This methodology facilitates a comprehensive evaluation of economic benefits and viability indicators across various operational frameworks in the field. The analysis implemented the Cost Per Liter (CPL) approach, incorporating diverse cost elements including initial capital expenditures, operational expenses, production costs, energy expenditures, internal rate of return, and other pertinent economic variables. The integrated HDH-PSS system achieved a daily production yield of 17.05 L/m2, representing a 180% increase over that of the standalone pyramid solar still (PSS). Utilizing current Egyptian energy tariffs, the economic assessment demonstrated that the hybrid HDH-PSS configuration produced potable water at an estimated unit cost of 0.045 $/L. However, the standalone PSS system exhibited superior cost efficiency at 0.016 $/L highlighting a key trade-off between production capacity and unit cost. Water production costs decrease proportionally with an extended system operational lifetime. Production costs increase correspondingly with higher rates. Costs decline significantly as system capacity expands, demonstrating substantial economies of scale. These findings confirm that larger-scale water treatment installations deliver considerably superior economic efficiency compared to smaller-capacity systems, highlighting the importance of strategic capacity planning for desalination project development.

Keywords: HDH, PSD, Hybrid system; Economic analysis, Low cost, System capacity, Water cost.

1. Introduction

Freshwater scarcity constitutes one of the most urgent global challenges of the 21st century, impacting over two billion people worldwide and posing serious risks to sustainable development across various sectors [1] [2] [3] [4]. The demand for water desalination technologies continues to grow due to increasing population, expanding urbanization, and worsening climate change effects [5]. As 75% of Earth's surface is water-covered, merely 3% of the planet's total water exists as fresh water, while the overwhelming majority (97%) consists of oceanic salt water. This represents a minimal percentage of available freshwater, prompting the development of desalination processes to convert seawater into potable water, though these methods require substantial energy inputs. Water scarcity has intensified due to population growth, industrial requirements, and increased consumption, creating a pressing global challenge. Concurrently, we face the urgent need to transition from fossil fuels, which drive climate change through greenhouse gas emissions, to renewable energy sources. Addressing these interconnected crises requires innovative solutions that simultaneously tackle both water scarcity and sustainable energy production to ensure environmental stability and resource security for future generations [6], [7]. Consequently, desalination of seawater has emerged as a reliable and cost-effective solution for providing freshwater for human consumption and agricultural and industrial applications. The demand for freshwater has increased substantially in recent decades, particularly in arid and isolated regions where conventional water sources are limited or unavailable. Recent research efforts have focused on developing hybrid water desalination systems to enhance productivity and achieve optimal operating conditions [8]. These systems combine multiple desalination technologies to maximize efficiency while minimizing energy consumption and operational costs. Several critical factors influence the economic viability of desalination technologies, including plant lifetime, capital costs of desalination equipment, interest rates, land acquisition costs, water transportation expenses to demand regions, feedwater quality, required product water quality, energy resource availability, pretreatment requirements for saline water, skilled labor availability, and plant capacity [9]. Plant location presents additional considerations, particularly for remote installations where the technology must be robust, maintenance requirements minimized, and operation simplified to ensure reliable performance. For remote desalination plants, energy consumption may be less critical than the system's compatibility with renewable energy sources, particularly solar energy, which can provide sustainable and economically viable power in isolated locations [10]. The integration of renewable energy sources has become increasingly important as the costs of freshwater production from desalination processes have decreased significantly in recent years. This cost reduction results from multiple factors, including declining equipment prices, reduced power consumption through technological improvements, and the widespread adoption of proven, mature desalination technologies [9].

This study introduces a detailed economic analysis of a novel tower-configured hybrid desalination system (HDH-PSS). The primary novelty of this study lies in three key aspects: (1) the unique tower-shaped design that compactly integrates an HDH unit with a pyramidal solar still (PSS), a configuration not extensively reported in the literature; (2) the utilization of waste engine oil as an intermediate heat transfer and storage medium to improve thermal continuity; and (3) a comprehensive comparative economic framework that directly evaluates the hybrid system's performance and cost against its standalone HDH and PSS components under identical experimental conditions.

A conceptual pilot unit was designed and evaluated to confirm the following:

1. Precise calculation of the desalinated water production cost across all systems.
2. Studying the effects of lifetime, interest rate, and system scale on water cost.

2. Description of the hybrid desalination system HDH – PSS

The hybrid desalination system (HDH-PSS) comprises two integrated units: a humidification-dehumidification system (HDH) as the primary unit, and a pyramid solar still (PSS) as the secondary unit. **Figure 1** shows a photograph of the complete hybrid system, displaying all essential components and their configuration. The HDH unit consists of two principal components: a humidifier and a dehumidifier. In contrast, the PSS unit incorporates a water basin and a transparent glass cover. Solar air heaters are employed to provide thermal energy for both air and engine oil, which subsequently heats the water in the system. The key parameters monitored throughout the experimental process included temperature variations, daily water yield, airflow rate, water flow rate, and incident solar radiation intensity. In the HDH unit, ambient air enters the solar air heater, where it undergoes preheating before being directed into the humidifier tank. Within the humidifier, the heated air becomes saturated with moisture from seawater that has been preheated through heat transfer from waste engine oil. Fresh water is produced through condensation within the dehumidification tank, where humid air releases its moisture content. The technical system specifications encompass detailed parameters for multiple interconnected components. The pyramid solar distiller was constructed with a water basin measuring 80×80×30 cm, utilizing a galvanized sheet with a thickness of 1.5 mm for the basin construction. The unit features a 5 mm thick cover glass and incorporates 5 cm thick glass wool insulation for thermal efficiency. The humidifier component consists of a tank with dimensions of 50×50×90 cm, constructed from a 1.5 mm thick galvanized sheet material. This component is equipped with five nozzle sprayers, each with a precise diameter of 1 mm for optimal spray distribution. The air heater specifications include side heating elements measuring 80×80×100 cm, with an inlet air diameter of 5 cm and a 0.5 HP air blower for circulation. The water heater and water cycle system feature an outer dimension of 60×60 cm and an inner dimension of 50×50 cm, powered by a 0.5 HP pump. Finally, the dehumidifier tank is dimensioned at 80×80×60 cm, constructed with 1.5 mm thick galvanized sheet material, and incorporates 5 cm thick glass wool insulation. For the PSS system, water is pumped from the water heater into the pyramid solar still it reaches the optimal water height required in the basin. The water level is precisely controlled and maintained using an automated level switch mechanism, ensuring consistent operational conditions within the PSS unit. The cost analysis and plant characterization conducted in this study encompasses three distinct desalination systems. The first system is the standalone (PSS), illustrated in **Figure 2**. The second system comprises the humidification-dehumidification (HDH) system with packing material (Loaf) and without packing material, also depicted in **Figure 1**. The third configuration represents the integrated hybrid system (HDH-PSS), which combines both technologies for enhanced performance. The system demonstrated an effective operational period of 15 hours of continuous production, from 8:00 AM to 11:00 PM, during August. This extended operation beyond peak solar irradiation hours was facilitated by the thermal inertia of the system components, particularly the heated waste engine oil and the water mass, which provided effective short-term thermal energy storage. The experimental protocol was designed to measure the total daily yield within this naturally achievable window. The productivity assessment period was standardized at 15 hours of continuous operation, commencing at 8:00 AM and concluding at 11:00 PM during August. This extended operational window was selected to capture the full spectrum of solar radiation availability and thermal dynamics throughout the day. The installation site for all three systems was designated as Suez City, Egypt, chosen for its optimal solar radiation conditions and representative desert climate characteristics. This location provides ideal testing conditions for solar-powered desalination technologies due to its high solar irradiance levels and minimal cloud cover during the experimental period.

Table 1 provides comprehensive details regarding the operational procedures, environmental conditions, and meteorological parameters encountered during the experimental campaign. This documentation includes ambient temperature ranges, humidity levels, wind speeds, and solar radiation intensities that influenced system performance throughout the testing period.

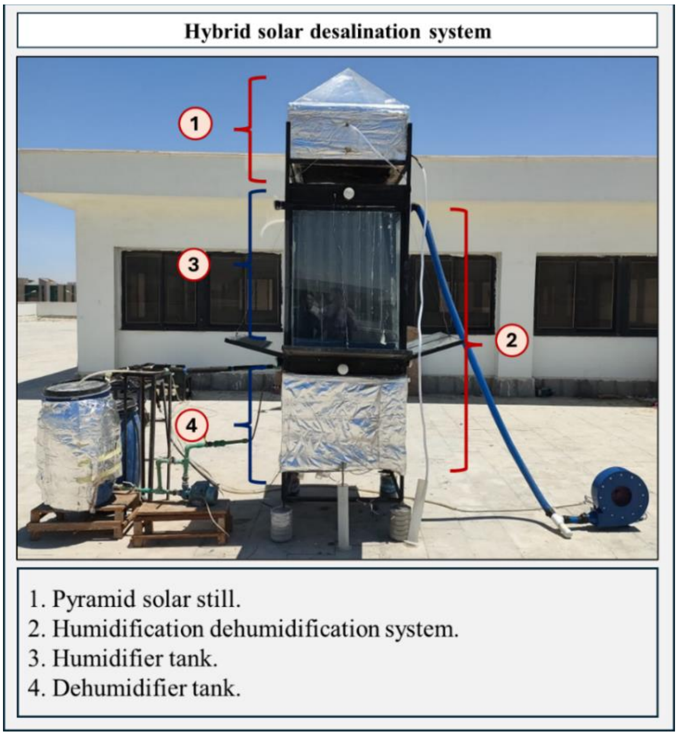

Figure. 1 The photograph of the hybrid solar desalination system.

Figure. 2 The photograph of the pyramid solar desalination systems.

Table 1. Operation conditions of systems.

Code	Desalination system	H_w	$\dot{m}w$	$\dot{m}a$	Types of packing material
		1.5 cm	0.223 kg/s	0.0442 kg/s	Loaf
PSS-0	PSS system	✓	-	-	-
HDH-1	HDH system	-	✓	✓	-
HDH-2	HDH system	-	✓	✓	✓
(PSS-0) -(HDH-2)	Hybrid system	✓	✓	✓	✓

2.1 Measuring techniques

During the experiment, many factors were tested, such as temperature, air speed, relative humidity, solar radiation, and freshwater productivity. The characteristics of the measuring instruments are shown in **Table 2.**

Table 2. Specifications of measuring devices.

Measuring devices	Jar (*mL*)	Digital flow meter (*L/min*)	Solar Power Meter (*W/m²*)	Digital anemometer (*m/s*)	K-type thermometer (*°C*)	Digital humidity meter (%)
Parameters	Freshwater	Feed water flow rate	Solar intensity	Airspeed	Temperature	Relative humidity
Model	Graduated laboratory	Digital FS300A	TENMARS TM-207	BENETECH GM8908	Type - K	UT333
Range	0:1000	1:60	0:2000	0:30	-200:1370	0:100

2.2 Uncertainty analysis

To calculate the measurement uncertainty, **Eq. 1** estimates the standard uncertainty by [11][12]. Table 3 lists the uncertainty of measurement devices.

$$\beta = \frac{\alpha}{\sqrt{3}} \tag{1}$$

Where:

α: the accuracy of the device.

β: the standard uncertainty.

In addition, **Eq. 2,3** can assist in assessing the uncertainty of any experimental outcome [13][14].

$$y = f\,(X_1, X_2, X_3, \ldots\ldots\ldots\ldots X_n) \tag{2}$$

$$\Delta y = \sqrt[2]{\left(\frac{\partial y}{\partial X_1}\Delta_1\right)^2 + \left(\frac{\partial y}{\partial X_2}\Delta_2\right)^2 + \left(\frac{\partial y}{\partial X_3}\Delta_3\right) + \cdots + \cdots + \left(\frac{\partial y}{\partial X_n}\Delta_n\right)} \tag{3}$$

Where y indicates the experimental result, y is the uncertainty associated with the result, reflecting the uncertainties associated with the independent variables X_1, X_2, X_3,... X_n.

Table 3. Accuracy and uncertainty of measuring devices.

Measuring devices	Jar	Digital flow meter	Solar Power Meter	Digital anemometer	K-type thermometer	Digital humidity meter
Accuracy	± 10 mm^3	± 3%	± 10 W/m	± 0.05 m/s	± 1%	± 1%
Uncertainty	5.773	0.0173	5.773	0.0288	0.00577	0.00577

3. Total cost of yield water

The cost of freshwater produced through the desalination system is typically calculated based on both fixed and variable operational expenses of the desalination facility. Fixed costs are determined by the initial capital investment and a plant depreciation factor, which varies according to several key parameters, including facility lifespan, investment amortization schedules, and prevailing financial conditions. Since depreciation methodologies are not standardized, these factors can differ significantly between countries and regulatory frameworks. Variable costs are closely linked to multiple operational factors: the plant's energy consumption requirements, local electricity pricing, labor expenses, routine maintenance expenditures, and the cost of chemicals needed for water pretreatment and post-treatment processes. These variable expenses often represent the most significant portion of total production costs and can fluctuate based on market conditions and operational efficiency. The overall economic viability of a desalination project, therefore, depends on optimizing both the initial capital structure and ongoing operational efficiency, while accounting for regional variations in regulatory, financial, and market conditions that influence the total cost of water production. The economic analysis conducted in this study was based on the Total Production Cost per Liter (TPL) methodology for evaluating distilled water production costs. The TPL encompasses the Total Annual Cost (TAC), which comprises several key economic components: Fixed Annual Cost (FAC), Sinking Fund

Factor (SFF), Annual Maintenance Cost (AMC), and Annual Salvage Value (ASV). Additional economic parameters relevant to desalination cost analysis were incorporated following the framework established in previous literature [reference needed]. This comprehensive cost structure allows for an accurate assessment of the economic viability of desalination systems by accounting for both capital-related expenses and operational expenditures over the facility's operational lifetime. The TPL metric provides a standardized basis for comparing different desalination technologies and system configurations on an equivalent cost-per-unit-production basis.

3.1 Initial cost classification and economic analysis

Initial cost classification for desalination systems, such as Humidification-Dehumidification (HDH) and pyramid solar still (PSS) desalination systems, involves categorizing expenses into capital equipment costs, installation costs, and auxiliary system costs. Initial expenses are treated as depreciable assets on the balance sheet, providing tax advantages through systematic depreciation over the asset's lifespan. Capital cost calculations for desalination systems depend primarily on two critical factors: the plant's production capacity and specific design characteristics. These costs encompass the procurement of major equipment, auxiliary systems, land acquisition, construction activities, management overhead, contingency reserves, and site preparation expenses. For the desalination configurations examined in this study, land requirements do not exceed 1.5 m^2 and require minimal site preparation. Consequently, in arid or remote regions where land costs are typically low, both land acquisition and site preparation expenses are considered negligible components of the total project cost. The comprehensive construction costs, including procurement, manufacturing, and installation expenses for both plant configurations (hybrid mode and separated system), are presented in **Table 4**. These cost estimates are derived from actual market prices and the assumptions outlined previously, with all values standardized to US dollars to ensure consistent economic comparison. Both desalination plant modes evaluated in this study are designed to operate exclusively on thermal solar energy as the primary heat source, reflecting the focus on renewable energy integration in desalination applications.

Table 4. Initial cost of desalination systems.

Item description	**Initial cost ($)**		
	PSS system	**HDH system**	**Hybrid system (HDH-PSS)**
Basin	70	-	70
Cover glass	25	-	25
Level switch	10	-	10
Glass wool	5	-	5
Dehumidifier Tank	-	35	35
Condenser coil	-	40	40
Tank of waste engine oil	-	75	75
Copper coil	-	55	55
Waste engine oil	-	20	20
Water pump	-	45	45
Air blower	-	65	65
Photovoltaic arrangement	-	150	150
Pipeline	-	20	20
Glass	-	130	130
Flexible duct	-	20	20

Packing material (Loaf)	-	15	15

3.2 Total annual cost

The Total Annual Cost (TAC) methodology serves as a cornerstone approach in engineering economics for systematically evaluating and comparing alternative investment options throughout their operational lifespans, as expressed in **Eq. 4** [4].

$$TAC = FAC + AMC - ASV \tag{4}$$

This formula calculates the equivalent uniform annual cost of owning and operating an asset. It's used to convert all costs and benefits associated with an investment on a consistent annual basis, making it easier to compare alternatives with different initial costs, lifespans, and maintenance requirements. Fixed Annual Cost (FAC): This represents the annual value of the initial capital investment. It's calculated by converting the initial purchase price into equivalent annual payments using the sinking fund factor or capital recovery factor. Annual Maintenance Cost (AMC): These are the recurring yearly costs for operation, maintenance, repairs, and other ongoing expenses needed to keep the asset functional. Annual Salvage Value (ASV): This is the annual benefit from the asset's residual value at the end of its useful life. It's subtracted because it represents a recovery in investment.

3.2.1 Fixed annual cost

Eq. 5 represents the fundamental relationship for converting initial capital investment into equivalent annual costs, forming the backbone of engineering economic analysis. It can be calculated by[15]:

$$FAC = IC \times CRF \tag{5}$$

Fixed Annual Cost (FAC) is the uniform annual payment that represents the annualized value of the initial investment. This converts a lump-sum expenditure into consistent yearly costs for comparison purposes. Initial Cost (IC) encompasses the total upfront capital investment required to acquire and install an asset. This includes purchase price, installation costs, setup expenses, and any other initial expenditure necessary to make the assets operational. Capital Recovery Factor (CRF) is a financial multiplier that accounts for both the recovery of the original investment and the earning of a specified rate of return over the asset's useful life. It incorporates the time value of money principle. The Capital Recovery Factor is calculated by **Eq. 6**[16]

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

Where:

- (i) represents the interest rate.
- (n) is the number of years in the asset's useful life.
- For the baseline economic analysis, an interest rate (i) of 12% was selected, reflecting a typical cost of capital for renewable energy projects in developing economies. The system lifetime (n) was assumed to be 10 years, a standard operational period for small-scale solar thermal systems, considering factors like component degradation and technological obsolescence.

3.2.2 Annual Maintenance Cost

Annual maintenance cost establishes a standard economic relationship where the Annual Maintenance Cost is estimated as 15% of the Fixed Annual Cost can be calculated by **Eq. 7** [17] [18]**.** This empirical rule provides a quick estimation method for budgeting ongoing operational and maintenance expenses based on the annualized capital investment. The 15% factor represents typical industry experience showing that annual maintenance costs generally range around this percentage of the equivalent annual capital cost for most engineering assets [19].

$$AMC = 0.15 \times FAC \tag{7}$$

3.2.3 Annual Salvage Value

Annual Salvage Value converts the future Salvage value into its equivalent annual worth, calculated by **Eq. 8**. The salvage value was estimated to be 10% of the initial capital cost, a common assumption for the residual value of specialized equipment at the end of its useful life [20]. The Sinking Fund Factor (SFF), **Eq. 9,** is a standard engineering economics function for converting a future value into a series of equivalent annual amounts, and its application is well-established in life-cycle cost analysis[21].

$$ASV = S \times SFF \tag{8}$$

$$SFF = \frac{i}{(1+i)^n - 1} \tag{9}$$

3.3 Calculation procedures

Cost Per Liter calculates the cost of distilled water per liter by dividing the total annual production cost by the annual average water output can be calculated by **Eq. 10** [22]. This formula determines the unit production cost, enabling economic evaluation of water distillation systems and comparison between different technologies or operational [23].

$$CPL = \frac{TAC}{WO} \tag{10}$$

4. Cost results analysis

Based on the previous HDH-PSS analysis, although solar-powered small-scale desalination systems exhibit higher costs per unit of fresh water produced, these costs remain significantly lower than those associated with freshwater transportation by truck. In many remote locations, fuel delivery reliability is poor, and transportation costs over long distances and inadequate road infrastructure are prohibitively expensive, as documented by [24]. Consequently, in isolated remote areas lacking electrical grid access and experiencing severe water supply shortages, economic considerations become secondary to basic water security needs. Under these circumstances, solar-powered desalination emerges as the most viable solution for small-capacity water treatment applications.

5. Economy of scale effect

From **Eqs. 4 and 10,** it is established that the capital cost of the system is directly proportional to system capacity, and since water cost is a function of these capital costs, it follows that water cost is also proportional to system capacity. Therefore, the relationship between the water costs of two different systems can be expressed through **Eq. 11**, which demonstrates how the ratio of water costs correlates with the ratio of their respective system capacities raised to a scaling exponent [25] [26].

$$\left(\frac{Water\ cost_{System1}}{Water\ cost_{System\ 2}}\right) = \left(\frac{System\ capacity_{System\ 1}}{System\ capacity_{System2}}\right)^m \tag{11}$$

Where:

- (m) is the index of the relationship between water cost and system capacity equal to 0.75 [26].

The widely recognized power-law relationship **Eq. 12** represents the standard capacity cost correlation employed in applications. This relationship enables estimating the capital investment required for a new facility with a specified capacity by utilizing the known initial cost data from an existing system of a different capacity. In cases where the scaling exponent R has not been empirically determined, typically apply a default value of 0.6. However, research indicates that the scaling exponent generally approaches 0.8, reflecting the specific economic characteristics and requirements of the water desalination system [25].

$$\left(\frac{Initial\ cost_{\ System1}}{Initial\ cost_{System\ 2}}\right) = \left(\frac{System\ capacity_{System\ 1}}{System\ capacity_{System2}}\right)^{R} \quad (12)$$

6. Results and Discussion.

6.1 Daily yield for different solar desalination systems

Figure 3 findings reveal a distinct productivity gradient among the evaluated desalination technologies, with daily water production rates spanning from 6.09 to 17.05 L/m^2. The pyramid solar still (PSS-0) functions as the reference system, generating a baseline daily yield of 6.09 L/m^2. This occurred at a water height of 1.5 *cm*. The utilization of humidification-dehumidification (HDH) technology substantially enhances system productivity. The HDH-1 configuration, operating without packing material, exhibits a 50% productivity increase relative to the baseline, achieving 9.03 L/m^2 daily output. Advanced system optimization was apparent in the HDH-2 configuration, which delivered a daily yield of 10.*96* L/m^2 and an 83% enhancement over the baseline PSS-0 system. This substantial performance gain results from packing material (loaf configuration) within the HDH-2 design. The highest outcome emerges from the hybrid desalination system (PSS-0 -HDH-2) system, which achieves a daily yield of 17.05 L/m^2. This configuration delivers an 183% improvement over the baseline system, demonstrating powerful synergistic effects when combining passive solar distillation with advanced HDH systems.

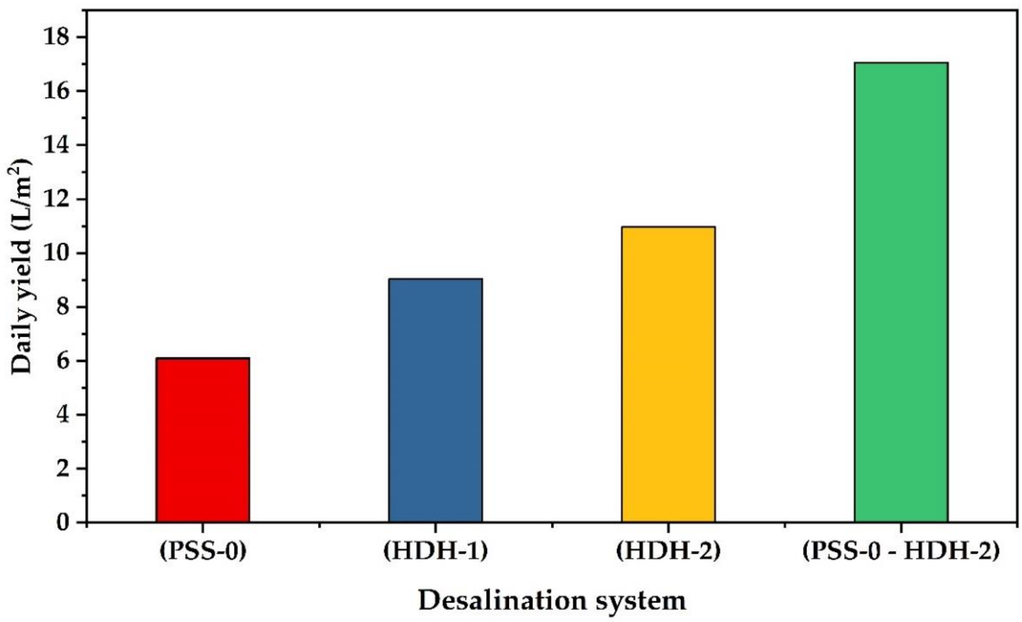

Figure 3. Daily yield comparison of different solar desalination systems.

6.2 Effect of system lifetime

Figure 4 presents a comprehensive economic evaluation demonstrating how the unit cost of water production *($/L)* varies with the system's operational lifetime for four different solar desalination configurations. The analysis reveals several critical economic insights that inform strategic decision-making for solar desalination investments. All systems exhibit a characteristic exponential decay in water cost as operational lifetime extends from 5 to 30 years. This trend reflects the systematic amortization of initial capital investments over extended operational periods, emphasizing the crucial importance of system durability and longevity for achieving economic viability in solar desalination applications. Pyramid Solar Still (PSS-0) demonstrates the lowest water costs across all operational timeframes, with unit costs ranging from 0.017 *$/L* at 5 years to *0.008 $/L*at 30 years. This superior economic performance stems from the system's inherent design simplicity, minimal initial capital requirements, and negligible maintenance demands, making it particularly attractive for cost-sensitive applications. The HDH-1 configuration (without packing material) and the HDH-2 system (with loaf packing material) both exhibit higher initial costs but follow similar declining economic trends. HDH-1-unit costs decrease substantially from 0.08 *$/L* to 0.039 *$/L*, while HDH-2 demonstrates a comparable reduction from 0.067 *$/L* to 0.033 *$/L* over the 30-year operational period. The moderately superior performance of HDH-2 directly reflects the thermal efficiency gains achieved through strategic packing material integration. The Hybrid desalination System (PSS-0 + HDH-2) exhibits intermediate economic performance characteristics, with unit costs declining from 0.050 *$/L* to 0.025 *$/L* across the evaluation period. Although this configuration delivers superior water production capacity compared to individual systems, the higher capital investment requirements result in elevated unit costs relative to the standalone PSS-0 system. The systematic convergence of all cost curves toward significantly lower values at extended operational lifetimes (20-30 years) indicates that long-term operational planning substantially improves the economic feasibility of more technologically complex systems. The relatively modest cost differentials between systems with a 30-year lifetime suggest that the enhanced performance advantages of advanced configurations may economically justify their higher initial capital investments for long-term installations. The most pronounced cost reductions occur within the initial 15 years of system operation, after which the rate of cost decrease diminishes considerably. This pattern suggests an optimal economic planning horizon of approximately 15 years for system payback calculations and return-on-investment analyses.

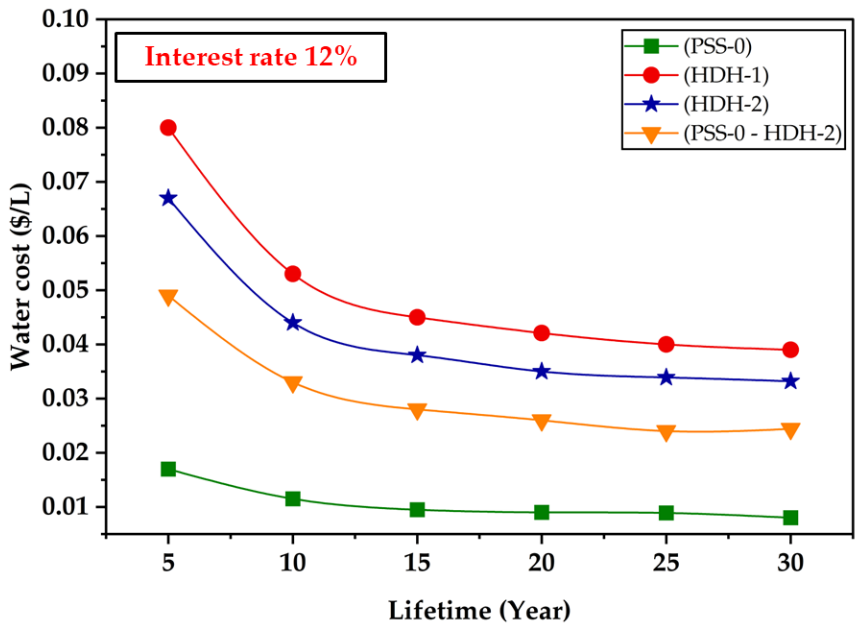

Figure 4. Variation of water cost with different lifetimes at a constant interest rate of 12%.

6.3 The Effect of the interest rate on water cost

Figure 5 illustrates the water cost sensitivity of different solar desalination technologies to varying interest rates, demonstrating how financing costs directly influence the unit cost of water production (*$/L*). The analysis spans interest rates from 10% to 20%, providing crucial insights for investment decision-making and comprehensive financial planning strategies. All systems exhibited a distinct positive linear correlation between interest rates and water production costs, indicating that higher financing costs substantially impact the economic viability of solar desalination projects. However, the magnitude of financial sensitivity varies significantly among different system configurations, revealing important distinctions in technology selection. (PSS-0) demonstrates remarkable economic resilience to fluctuations in interest rates. Unit costs increase minimally from 0.010 *$/L* at 10% interest to 0.016 *$/L*at 20% interest, representing the smallest absolute cost variation among all evaluated systems. This exceptional financial stability stems from the system's inherently low capital requirements and simplified design architecture, making it relatively insensitive to prevailing financing conditions. HDH Systems exhibits pronounced sensitivity to interest rate variations. HDH-1 (without packing material) demonstrates the steepest cost escalation trajectory, rising from 0.048 *$/L* to 0.074 *$/L* across the interest rate spectrum—representing a substantial 54% increase. HDH-2 (with loaf packing material) shows similar but moderately tempered sensitivity, with costs increasing from 0.040 *$/L* to 0.062 *$/L*, corresponding to a 55% cost elevation. This heightened sensitivity directly reflects the substantial capital investments and complex infrastructure requirements inherent in the implementation of HDH technology (PSS-0 + HDH-2) displays intermediate sensitivity characteristics, with unit costs rising from 0.030 *$/L* to 0.045 *$/L* as interest rates increase from 10% to 20%. This represents a 50% cost increase, strategically positioning the hybrid system between the highly stable PSS-0 configuration and the more financially volatile individual HDH systems. The diverging cost trajectories underscore the critical importance of securing favorable financing terms for capital-intensive desalination systems. In low-interest-rate environments (10-12%), the superior performance advantages of advanced HDH and hybrid systems may economically justify their higher initial costs. However, at elevated interest rates (18-20%), the economic advantage shifts decisively toward the simpler PSS-0 system, which maintains cost competitiveness regardless of financing conditions. Comprehensive analysis reveals that prevailing interest rate environments significantly influence optimal technology selection strategies. In low-interest economic scenarios, investors should consider advanced systems for their superior water production capabilities and long-term performance benefits. Conversely, high-interest environments strongly favor simple, low-capital systems that minimize financing burden while maintaining operational effectiveness and reliability.

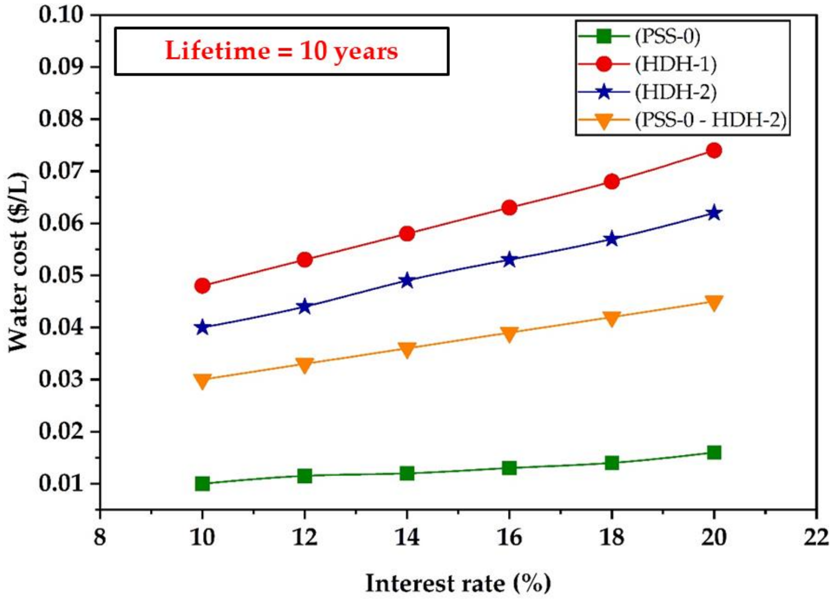

Figure 5. illustrates the water cost sensitivity of different solar desalination technologies to varying interest rates.

6.4 Water cost for different desalination systems

Figure 6 presents a dual-axis analysis comparing daily water yield with corresponding unit water costs for four solar desalination systems under standardized economic conditions (12% interest rate, 10-year lifetime). The analysis reveals a clear inverse relationship between water production capacity and unit costs, demonstrating the economic benefits of higher-yield systems. This relationship illustrates the fundamental principle that increased productivity leads to improved cost-effectiveness in solar desalination applications. (PSS-0) serves as the baseline configuration, producing 6.09 L/m^2 daily at the lowest unit cost of 0.012 *$/L.* Although offering modest water production, this system provides exceptional economic efficiency owing to its minimal capital requirements and operational simplicity. HDH-1 System (without packing material) demonstrates a 50% increase in daily yield to 9.03 l/m^2, but experiences a substantial cost penalty, reaching a peak unit cost of 0.054 *$/L*. This represents the highest cost per liter among all configurations, indicating owing to the productivity gains do not offset the increased capital and operational expenses under these financial conditions. HDH-2 System (with loaf packing material) achieves a 10.96 L/m^2 daily yield while maintaining a more favorable unit cost of 0.043 *$/L* compared to HDH-1. Packing material enhancement improves both productivity and cost-effectiveness, demonstrating the value of system optimization in HDH configurations. Hybrid System (PSS-0 + HDH-2) delivers the highest water production at 17.05 L/m^2 daily with a moderate unit cost of 0.033 *$/L*. This configuration achieves the optimal balance between performance and economics, providing nearly three times the water output of the baseline system while maintaining reasonable cost levels.

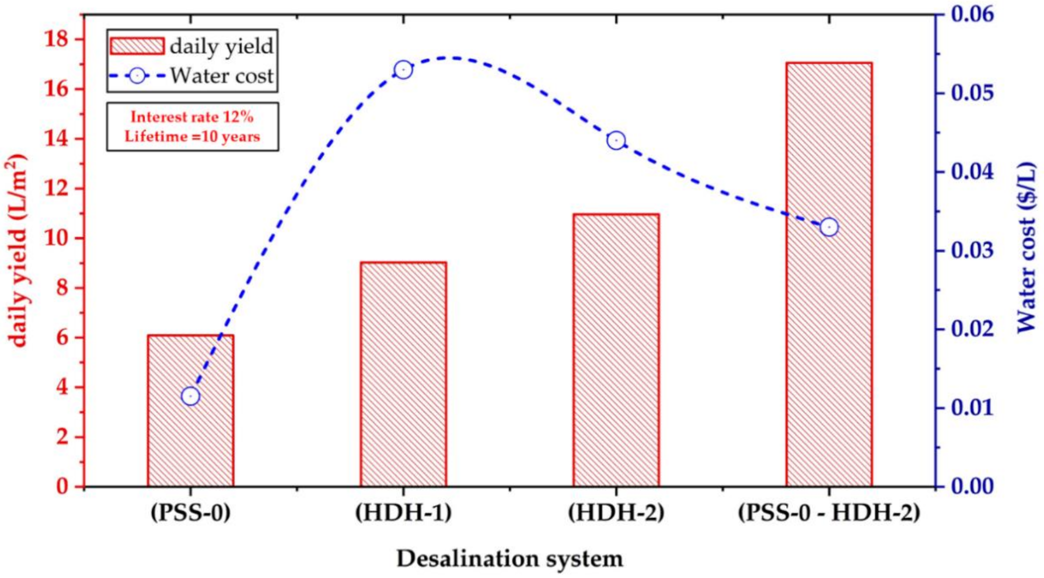

Figure 6. Comparative analysis of daily water yield and unit cost for solar desalination systems at a 12% interest rate and 10-year lifetime.

6.5 Effect of system scale on water cost.

Figure 7 compares water desalination systems (PSS-0), (HDH-1), (HDH-2), and (PSS-0 – HDH-2), showing water cost and initial cost versus system capacity. At very low capacities, PSS-0 has extremely high-water costs that drop sharply, while HDH systems maintain more stable, lower costs. All systems converge to similar water costs (0.001:0.002$ $\$/m^3$) around 0.4: 0.5 m^3/day capacity. Initial costs increase with capacity for all systems, with (HDH-1) showing the steepest rise to 55000 *$* at 2 m^3/day. HDH systems are more cost-effective for small-scale applications, while PSS-0 becomes competitive at larger capacities due to economies of scale.

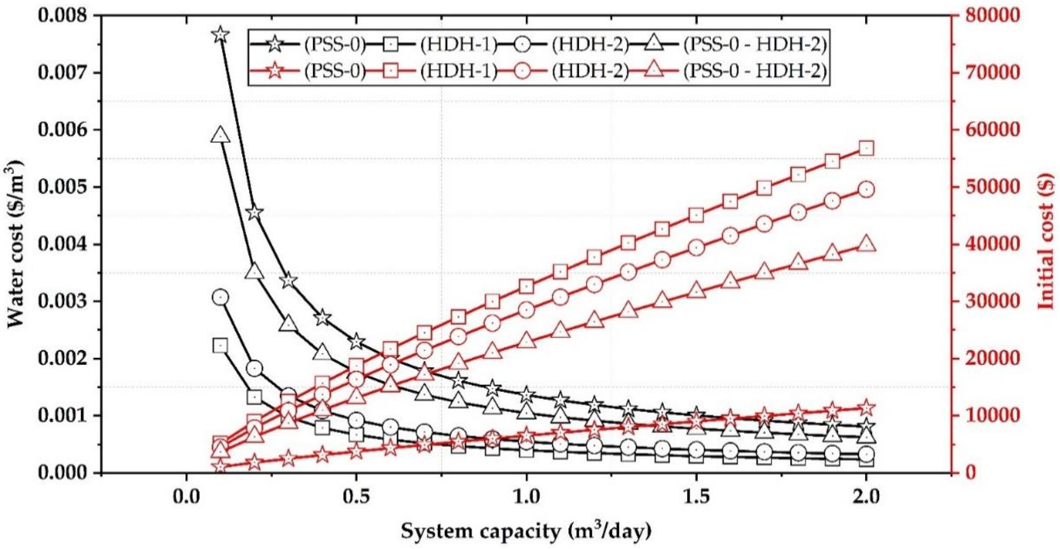

Figure 7. Capital cost and water cost for hybrid (PSS-HDH) desalination technologies at various system capacities.

7. Conclusions

The key findings demonstrate a clear trade-off between productivity and unit cost. The hybrid HDH-PSS system achieved a superior daily water production of 17.05 L/m^2, which represents a 180% increase over the standalone PSS system (6.09 L/m^2). However, this enhanced productivity came at a higher unit cost. Under baseline economic conditions (a 10-year lifetime and a 12% interest rate), the cost per liter (CPL) for the hybrid system was estimated at $0.045, compared to 0.016 *$* for the standalone PSS system. This highlights that while hybridization significantly boosts yield, it introduces higher capital costs that impact economic efficiency. The economic evaluation further revealed three critical factors governing system viability:

1. The unit water cost exhibited a strong inverse relationship with the operational lifespan. Extending the system lifetime from 5 to 30 years resulted in a substantial reduction in CPL for all configurations, underscoring the long-term economic attractiveness of these investments.
2. The analysis showed a direct positive correlation between interest rates and water production costs. The HDH-based systems were particularly sensitive to financing costs, indicating that securing favorable financial terms is crucial for the economic feasibility of more capital-intensive technologies.
3. A significant scaling effect was confirmed, wherein increasing the system capacity led to a pronounced decrease in the unit cost of water. This suggests that large-scale implementations would benefit from substantially improved cost-effectiveness.

The standalone PSS system emerges as the most economically efficient solution for small-scale, cost-sensitive applications where maximum water output is not the primary constraint. Conversely, the hybrid HDH-PSS system is better suited for scenarios requiring higher production capacity, provided that the higher initial investment is justified by the water demand. The choice between systems should therefore be guided by careful consideration of local water needs, available capital, financing conditions, and the intended project lifespan. For future work, integrating thermal energy storage could be explored to extend operational hours and further improve the productivity and economic value of the hybrid system.

Nomenclature:

Characters	Explanation, unit
H	Height, cm
i	Interest rate, %
n	Number of years

Abbreviations:

Description	Symbols
PSS	Pyramid solar still
HDH	Humidification De-humidification
HP	Hours power
TAC	Total Annual Cost
FAC	Fixed Annual Cost
AMC	Annual Maintenance Cost
ASV	Annual Salvage Value
SFF	Sinking fund factor
WP	Water production

Subscripts:

Symbol	Description
w	Water
a	Air
α	The accuracy of the device.
β	The standard uncertainty.

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