



RESEARCH ARTICLE

Comparative Techno-Economic Assessment of Solar Thermal Humidification-Dehumidification and PV-Driven Reverse Osmosis for Inland Brackish Water Desalination

*¹Ch. Mohammad Akram, ²Govind Nandipati

¹* Research Scholar, Department of Mechanical Engineering, Acharya Nagarjuna University, Guntur, Andhra Pradesh - 522510, India.

²Associate Professor, Department of Mechanical Engineering, RVR & JC College of Engineering, Chowdavaram, Andhra Pradesh - 522019, India.

ABSTRACT

Inland brackish-water desalination requires systems that deliver reliable freshwater under variable solar conditions while minimizing electrical energy demand, levelized cost of water (LCOW), and brine-management constraints. This study presents a 12-month pilot-scale comparison of solar thermal humidification–dehumidification (HDH) and photovoltaic-driven reverse osmosis (PV-RO) in an inland high-solar environment. Under baseline brackish groundwater conditions, PV-RO proved superior as a primary desalination pathway. PV-RO achieved a 57.1% higher area-normalized freshwater yield (28.9 vs. 18.4 L m⁻² day⁻¹) and reduced specific electrical energy consumption by 44.7% (6.8 vs. 12.3 kWh m⁻³). Product water quality was also stronger for PV-RO, with 98.3% TDS removal compared with 95.8% for HDH. Utilizing a capacity-scaled framework for a 1,000 m² deployment, PV-RO delivered a lower projected LCOW (1.38 USD m⁻³) compared to HDH (2.61 USD m⁻³). However, rigorous thermodynamic closure—including an empirical HDH Gain-Output Ratio (GOR) of 2.06—and solution-diffusion modeling ($J_w = A(\Delta P - \Delta \pi)$) redefine this performance hierarchy at elevated salinities. Sensitivity mapping defines a quantitative tipping point: scaling-induced degradation of RO permeability drives its LCOW above the thermodynamically stable HDH baseline of 2.61 USD m⁻³. Consequently, this study proposes a synergistic inland deployment architecture, utilizing PV-RO for primary recovery and reserving HDH as a salinity-resilient, secondary brine concentrator to achieve decentralized Zero Liquid Discharge (ZLD).

Keywords: Solar desalination; Photovoltaic reverse osmosis; Humidification–dehumidification; Water yield; Energy efficiency; Techno-economic assessment; Levelized cost of water; Brine concentration; Zero liquid discharge

INTRODUCTION

1.1 Global Water Scarcity and The Sustainability Challenge of Desalination

Water scarcity has become one of the defining environmental and developmental challenges of the twenty-first century [1–3]. Population growth, urban expansion, industrialization, and climate variability are intensifying pressure on already limited freshwater resources, particularly in arid, semi-arid, and seasonally water-stressed regions [4]. In many such areas, conventional surface-water and groundwater supplies are increasingly unable to meet domestic, agricultural, and industrial demand, thereby increasing reliance on non-conventional water resources such as desalination [5]. Global institutions increasingly emphasize that integrating such desalination infrastructure is critical for mitigating long-term water scarcity risks on a macroeconomic scale [6].

Although desalination is now widely recognized as an essential technology for augmenting freshwater supply, conventional desalination remains closely associated with high energy demand and substantial environmental burden when powered by fossil-fuel-based energy systems[7,8].

*Research Scholar, Department of Mechanical Engineering, Acharya Nagarjuna University, Guntur, Andhra Pradesh - 522510, India.
Email-id: akram.anucet@gmail.com

Corresponding Author: Ch. Mohammad Akram
Research Scholar, Department of Mechanical Engineering, Acharya Nagarjuna University, Guntur, Andhra Pradesh - 522510, India.

DOI: <https://doi.org/10.63856/ijis/v2i10/01>

How to cite this article: Akram, M., (2026). Comparative Techno-Economic Assessment of Solar Thermal Humidification-Dehumidification and PV-Driven Reverse Osmosis for Inland Brackish Water Desalination. *International Journal of Integrative Studies*, 2(10), 01-28.

Source of support: Nil

Conflict of interest: None.

Received: 10/09/2026 **Revised:** 20/09/2026 **Accepted:** 25/09/2026 **Published:** 01/10/2026

Thermal desalination and electrically driven membrane desalination are both capable of producing high-quality freshwater, but operating costs, greenhouse gas emissions, and dependence on centralized energy infrastructure often constrain their large-scale deployment [9,10]. As a result, improving freshwater access without intensifying energy use and environmental impact has become a central challenge in the water–energy nexus [11].

1.1 Solar Desalination as a Sustainable Pathway

Among renewable energy sources, solar energy is especially attractive for desalination because of its abundance, renewability, and strong overlap with water-stressed regions [12,13]. Solar-driven desalination offers the potential to produce freshwater with reduced carbon emissions while enabling decentralized operation in remote, infrastructure-limited settings [14,15]. Moreover, transitioning to solar-driven desalination is increasingly recognized as a vital mechanism for climate change mitigation and advancing global sustainable development goals [16]. These advantages have made solar desalination increasingly relevant as a sustainable strategy for freshwater production in regions where conventional energy-intensive desalination may be economically or environmentally burdensome [17,18].

The present study is built on this premise and focuses on two major solar desalination pathways: solar thermal humidification–dehumidification (HDH) and photovoltaic-driven reverse osmosis (PV-RO), and frames their comparison around energy use, freshwater productivity, and cost-effectiveness over a 12-month pilot-scale monitoring period.

1. Literature Review: Solar Thermal HDH Systems

Solar thermal HDH systems emulate the natural hydrological cycle by using solar-derived heat to promote evaporation and subsequent condensation [19]. In this approach, saline water is brought into contact with a heated air stream or a heated working medium, resulting in moisture transfer and, eventually, freshwater recovery through condensation [20]. HDH systems have attracted considerable attention because of their conceptual simplicity, relatively low mechanical complexity, and suitability for decentralized and small-scale applications [21,22].

The literature, however, shows that HDH performance is highly sensitive to system configuration, humidifier and dehumidifier design, air–water contact effectiveness, and thermal losses [22,23]. Freshwater productivity can vary substantially depending on whether the system is air-heated, water-heated, or thermally integrated with storage or heat recovery [24]. As a result, while HDH remains attractive for remote or low-throughput applications, its energy efficiency and water yield are often lower than those of membrane-based desalination methods unless the thermal system is carefully optimized [25,26].

1.2 Literature Review: Photovoltaic-Driven Reverse Osmosis Systems

Photovoltaic-driven reverse osmosis (PV-RO) has emerged as one of the most promising renewable-energy desalination pathways because it combines the maturity of membrane desalination with direct solar-electric power conversion [27,28]. Continuous advancements in membrane materials and module design have further enhanced the fundamental separation efficiency and viability of these processes [29]. In PV-RO systems, solar radiation is converted into electricity through photovoltaic modules and used to drive a high-pressure membrane process. Compared with thermally driven desalination, PV-RO generally benefits from higher conversion efficiency, modularity, and the ability to produce high-quality freshwater with relatively low specific energy demand [30,31].

Existing studies have shown that PV-RO is particularly attractive for high-solar environments and decentralized inland or coastal applications, especially when freshwater demand is moderate, and grid dependence is undesirable [32,33]. At the same time, the literature also indicates that PV-RO performance depends on feedwater chemistry, recovery ratio, membrane characteristics, and the stability of solar power availability [34,35]. Consequently, although PV-RO is increasingly viewed as a leading solar desalination option, its field performance remains strongly context-dependent [36].

1.3 Research Gap and Novelty

Despite the individual maturity of solar thermal humidification-dehumidification (HDH) and photovoltaic-driven reverse osmosis (PV-RO), robust comparative frameworks evaluated under unified, long-duration field conditions remain critically scarce. Existing literature frequently evaluates these pathways in isolation or relies on disparate climatic and economic assumptions, resulting in deep analytical fragmentation [28,37,38]. Crucially, contemporary studies often reduce the comparison between thermal and membrane pathways to static performance metrics—such as baseline specific energy consumption (SEEC)—framing them merely as competing technologies. What is fundamentally absent from the literature is a quantitative, thermodynamics-based delineation of their transition boundaries. For inland brackish-water desalination, where high hardness and strict brine disposal regulations pose severe constraints [39–42], relying on static cost projections fails to capture the dynamic "tipping point." Specifically, existing models fail to quantify the exact threshold where the osmotic pressure and scaling penalties of membrane-based systems mathematically intersect with the relatively invariant, latent-heat-driven limits of thermal systems for Zero Liquid Discharge (ZLD) applications [6,43,44].

The novelty of the present study lies in bridging this critical analytical gap through a dual-tiered framework.

First, it provides a 12-month, side-by-side empirical assessment of pilot-scale HDH and PV-RO systems under highly variable, inland solar conditions. Second, it transcends traditional empirical reporting by integrating rigorous thermodynamic closure—validating internal latent heat recovery—and solution-diffusion membrane transport modeling ($J_w = A(\Delta P - \Delta \pi)$) into a projected Levelized Cost of Water (LCOW) sensitivity matrix.

By mathematically defining the specific threshold where scaling-induced permeability degradation forces PV-RO operational costs above the stable HDH economic baseline, this study shifts the scientific narrative from technological competition to synergistic architecture. Ultimately, this work provides actionable, physics-backed deployment guidance, establishing the precise thermodynamic bounds where PV-RO serves as the primary freshwater pathway and where HDH becomes an economically essential secondary brine-concentrator to achieve decentralized ZLD.

1.4 Objectives and Contribution

To address this critical gap, this study compares solar thermal HDH and PV-driven RO at pilot scale under common field conditions, evaluating their relative performance in freshwater productivity, energy demand, and economic viability. Both systems were operated simultaneously under the high-solar, seasonally water-stressed conditions of Vijayawada, India.

The specific contributions of this work are threefold:

1. **Empirical Benchmarking:** Provide robust, year-long field evidence contrasting area-normalized freshwater yield, specific energy consumption, and verified product-water quality under dynamically varying seasonal irradiance.
2. **Comprehensive Techno-Economic Assessment:** Transition beyond simplified electricity-related

variable operating costs by developing a hybrid LCOW scenario framework that accounts for the distinct capital expenditure (CAPEX) profiles, membrane replacement schedules, and maintenance demands of both pathways, integrating empirical pilot data with benchmarked commercial assumptions.

3. **Thermodynamic Boundary Definition:** Utilize multi-variable sensitivity mapping to identify precise salinity and solar-resource thresholds that dictate when PV-RO is the optimal primary pathway, and when HDH becomes economically essential as a Secondary brine-concentrator for ZLD architectures [45,46].

Together, these contributions directly link the study's methodology to the results presented in Section 2, ensuring that the field-scale data, techno-economic modeling, and tipping-point analysis provide actionable insights for inland solar desalination deployment.

1. Materials and Methods

2.1 Study area and climatic setting

The solar desalination systems were installed in Vijayawada, Andhra Pradesh, India, an inland tropical location characterized by strong solar availability and seasonal water stress. The site was selected because it provides a suitable field setting for evaluating solar desalination under conditions relevant to water-limited, solar-rich regions. During the study period, the average daily solar irradiance was approximately $5.82 \text{ kWh m}^{-2} \text{ day}^{-1}$, with seasonal variation across the year. The experimental campaign spanned 12 consecutive months to assess the effect of seasonal solar-resource variability on desalination performance. The principal site and climatic characteristics of the study area are summarized in **Table 1**.

Parameter	Value / Description
Study location	Vijayawada, Andhra Pradesh, India
Approximate coordinates	16.51° N, 80.65° E
Climatic classification	Tropical savanna / wet-dry climate (Köppen-Geiger Aw)
Study duration	12 months
Mean annual air temperature	~28.2 °C
Annual rainfall	~974 mm
Average daily solar irradiance during the study	$5.82 \text{ kWh m}^{-2} \text{ day}^{-1}$
Seasonal solar irradiance range during the study	$4.3\text{--}7.1 \text{ kWh m}^{-2} \text{ day}^{-1}$
Site relevance	High solar resource and seasonal water stress are suitable for solar desalination

Table 1: Site and climatic characteristics of the study area

2.2 Feedwater source and characteristics

The brackish groundwater (moderately saline, with near-neutral to slightly alkaline pH and elevated hardness), collected from borewells in peri-urban regions of

Vijayawada, is consistently fed to both the HDH and PV-RO systems for comparative analysis. The feedwater characteristics are summarized in **Table 2**.

Parameter	Representation/Range
Feedwater source	Brackish groundwater of the peri-urban Vijayawada borewells
pH	7.6-7.9
Total Dissolved Solids (TDS)	1072-1356 mg L ⁻¹
Hardness (as CaCO₃)	499-556 mgL ⁻¹
Feedwater class	Moderately saline, high-hardness groundwater
Technical relevance for PV-RO	Scaling and fouling risk for RO membrane operation
Technical relevance for HDH	Scaling/deposition risk on thermal-loop, humidifier, and condenser surfaces
Justification for feedwater selection	Representative of inland brackish-water conditions at the study site

Table 2: The study's Feedwater characteristics

2.3 Experimental systems

Two solar desalination configurations were investigated: solar thermal humidification–dehumidification (HDH) and photovoltaic-driven reverse osmosis (PV-RO). These systems were selected because they represent two distinct solar-energy utilization routes, namely solar-to-thermal

desalination and solar-to-electrical membrane desalination. To objectively assess their performance under identical conditions, both systems were installed as pilot units and operated simultaneously in the same field environment. The principal design features of the two pilot desalination systems are summarized in **Table 3**.

Parameter	Solar thermal HDH	PV-driven RO
Solar-energy pathway	Solar thermal	Solar photovoltaic
Desalination mechanism	Humidification–dehumidification/evaporation–condensation	Pressure-driven membrane separation
Main process route	Solar heat → evaporation → humidification → condensation	Solar electricity → pumping pressure → membrane permeation
Main components	Solar collector, feedwater circulation line, humidifier, dehumidifier/condenser, feed pump, freshwater collector	PV array, controller/inverter, high-pressure pump, RO membrane module, permeate collector, reject-brine outlet
Feedwater	Brackish groundwater	Brackish groundwater
Active solar collection area	2.0 m ²	2.0 m ²
Membrane type	Not applicable	Spiral-wound polyamide thin-film composite membrane
Typical salt rejection	Not applicable	High-rejection brackish-water RO membrane
Operating pressure	Thermally driven	8–10 bar
Maximum membrane pressure	Not applicable	10 bar
Nominal recovery ratio	Not applicable in the membrane sense	25%
Product-water pathway	Condensation of humidified vapor	Membrane permeation
Concentrate/brine pathway	Blowdown or concentrated residual stream	RO reject stream
Main technical constraint	Thermal losses, humidifier/dehumidifier efficiency, heat recovery	Scaling, fouling, osmotic pressure, pressure limitation
Deployment relevance	Salinity-resilient Secondary or low-throughput pathway	Primary freshwater-production pathway for moderate brackish groundwater

Table 3: Design and operating characteristics of the pilot-scale HDH and PV-RO systems

2.3.1 Solar thermal HDH system

The HDH system employed solar thermal energy to support an evaporation–condensation desalination process. In this configuration, solar heat was used to raise the temperature of the working stream and enhance humidification of saline feedwater. The resulting moisture-laden stream then entered the dehumidification Section,

where vapor condensed and was recovered as freshwater. The principal components of the HDH unit were solar collectors, a thermal loop, a humidification Section, a dehumidification/condensation Section, and a product-water collection unit. This system was selected because of its comparatively simple design and suitability for decentralized, small-scale desalination[21,47].

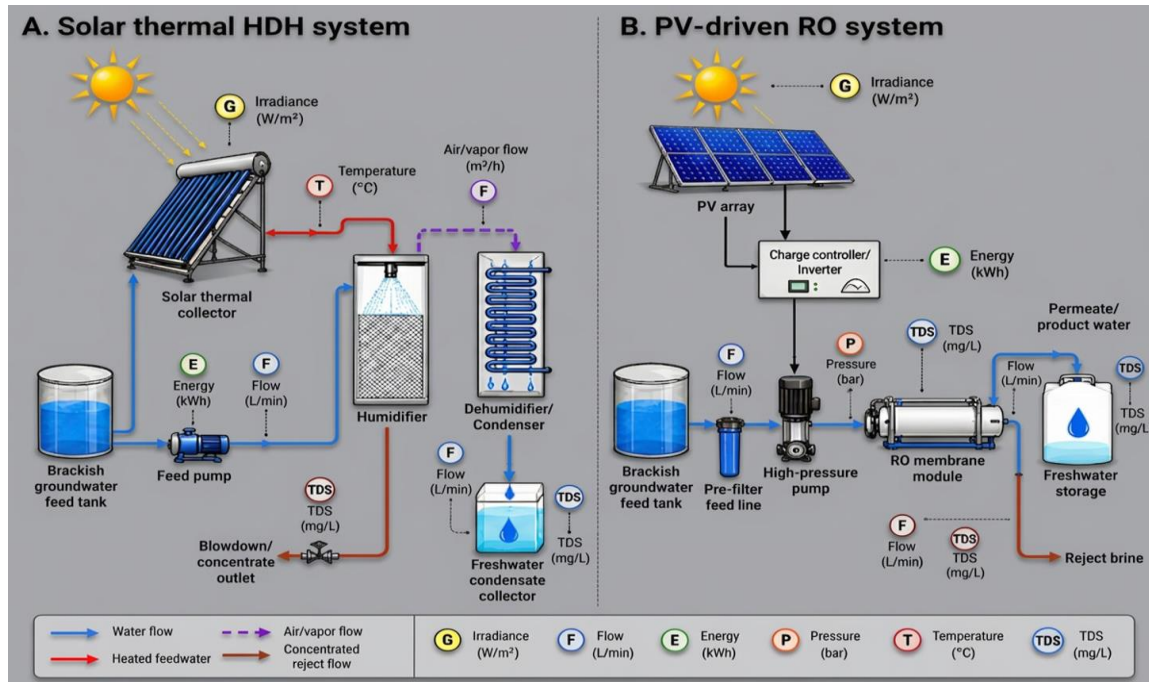


Figure 1: Experimental setup of the pilot-scale solar thermal HDH and PV-driven RO systems

2.3.2 PV-driven RO system

The PV-RO system used photovoltaic panels to convert solar radiation into electricity for membrane desalination. The electrical output from the PV subsystem powered a pressure-assisted reverse osmosis unit, in which feedwater was forced through a semi-permeable membrane to produce freshwater and reject a concentrated brine stream. The principal components of the PV-RO unit were a PV array, control and power-conditioning components, a high-pressure pump, an RO membrane module, and freshwater storage. This configuration was chosen because of its relatively high efficiency and strong suitability for solar-powered water production in high-irradiance environments [48,49]. Schematic representation of the experimental setup of solar thermal HDH and PV-driven RO systems is provided in Figure 1

2.4 Instrumentation, Calibration, and Measurement Uncertainty

Both systems were monitored using a daily field-instrumentation framework. Solar irradiance was measured using a pyranometer, freshwater production using a flow meter, electrical energy consumption using a smart energy meter, and product water quality using conductivity/TDS, pH, and hardness measurements. These variables were selected because they directly capture the solar resource, water productivity, energy demand, and desalination effectiveness of the systems. The measured parameters, associated instrumentation, units, and monitoring frequency are listed in Table 4.

Parameter	Instrument/method	Unit	Monitoring frequency	Purpose
Solar irradiance	Pyranometer	$\text{kWh m}^{-2} \text{ day}^{-1}$	Daily	Quantification of available solar energy
Freshwater output	Flow meter / calibrated collection volume	L day^{-1}	Daily	Measurement of freshwater production
Energy consumption	Smart energy meter	kWh	Daily	Measurement of system energy use

Product-water salinity	Conductivity/TDS meter	$\mu\text{S cm}^{-1} / \text{mg L}^{-1}$	Daily or scheduled sampling	Assessment of desalination effectiveness
Product-water pH	pH meter	pH units	Scheduled sampling	Product-water quality assessment
Product-water hardness	Laboratory/titrimetric method	mg L^{-1} as CaCO_3	Scheduled sampling	Assessment of hardness reduction and scaling relevance
Operating pressure for RO	Pressure gauge/pressure sensor	Bar	Daily or operational check	Verification of membrane operating range
Ambient temperature	Thermometer/weather station	$^{\circ}\text{C}$	Daily or scheduled logging	Climatic context for field operation

Table 4: Measured parameters, instruments, units, and monitoring frequency

To improve measurement reliability, the instrumentation framework was paired with calibration and quality-control practices. The pyranometer was assumed to follow traceable solar-radiation calibration practice; the flow meter was verified before operation, the energy meter was treated as a Class 1 electrical meter, and the conductivity

meter was calibrated using standard conductivity solutions. Measurement uncertainty was treated at the system level, with unresolved minor errors absorbed into the daily integrated monitoring basis. The calibration basis, uncertainty ranges, and quality-control protocol adopted for the instrumentation are summarized in **Table 5**.

Instrument/parameter	Calibration or verification basis	Accuracy/uncertainty	QA/QC protocol
Pyranometer	Traceable solar-radiation calibration	$\pm 2\text{--}5\%$ for daily integrated irradiance	Range screening; removal of negative or physically implausible values
Flow meter/collection volume	Pre-commissioning volumetric verification	$\pm 1\%$ of reading	Periodic verification against known collection volume
Smart energy meter	IEC Class 1 equivalent	$\pm 1\%$ of reading	Daily consistency check against operating records
Conductivity/TDS meter	Standard conductivity calibration solutions	$\pm 1\%$ of reading	Calibration before measurement sessions; spike and drift screening
pH meter	Standard buffer calibration	± 0.1 pH unit	Buffer verification before sampling
Hardness analysis	Standard titration or laboratory protocol	Method-dependent	Duplicate or periodic laboratory verification
RO pressure gauge/sensor	Factory calibration or pressure-reference check	Instrument-dependent	Operational range verification
Missing-data handling	Not applicable	Not applicable	Short isolated gaps excluded from primary metrics unless verified; multi-day gaps excluded from aggregation
Outlier treatment	Physical plausibility and range screening	Not applicable	Values inconsistent with system operation removed after QA/QC review

Table 5: Instrument calibration, uncertainty, and quality-control protocol

TDS was monitored using a conductivity/TDS meter during routine field operation, while pH and hardness were measured through scheduled water-quality sampling. This separation was adopted because salinity changes are directly linked to daily desalination performance, whereas pH and hardness were used as periodic product-water quality and scaling-relevance indicators.

To improve reliability, all instruments were calibrated or verified prior to operation and periodically checked during the monitoring campaign. Instrument-level uncertainties

were used to estimate uncertainty in derived indicators such as freshwater yield, SEEC, and electricity-related operating cost. Derived uncertainty was treated using standard propagation from measured variables.

For freshwater yield:

$$\frac{\delta Y}{Y} = \sqrt{\left(\frac{\delta V_w}{V_w}\right)^2 + \left(\frac{\delta A_c}{A_c}\right)^2}$$

For specific energy consumption:

$$\frac{\delta SEEC}{SEEC} = \sqrt{\left(\frac{\delta E}{E}\right)^2 + \left(\frac{\delta V_w}{V_w}\right)^2}$$

For electricity-related variable operating cost:

$$\frac{\delta C_{e,var}}{C_{e,var}} = \sqrt{\left(\frac{\delta SEEC}{SEEC}\right)^2 + \left(\frac{\delta C_e}{C_e}\right)^2}$$

where δ denotes measurement uncertainty in the respective variable.

2.5 Monitoring protocol, data completeness, and quality control

Monitoring was conducted on a daily basis throughout the year. The measured variables were solar irradiance, freshwater output, electrical energy use, and product-water

salinity. Daily logging was selected to provide adequate temporal resolution while remaining practical for long-duration pilot operation. These daily data were subsequently used to calculate freshwater yield, specific energy consumption, and electricity-related variable cost.

A valid operating day was the one for which all principal variables were available. Data quality control included range screening to remove physically implausible values, consistency checking across monitored variables, and exclusion of extended missing periods from monthly or annual aggregation. Short isolated gaps, when unavoidable, may be addressed through limited interpolation for visualization only; however, all comparative performance metrics were derived from the valid monitored dataset. The overall experimental and analytical workflow followed in the present study is illustrated in **Figure 2**.

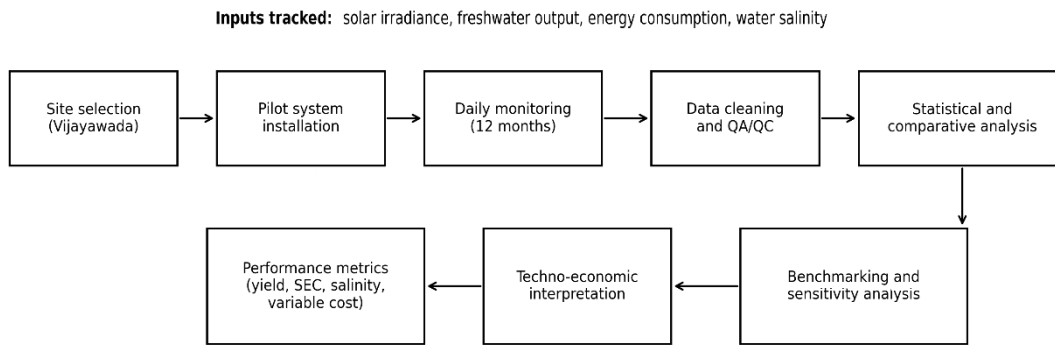


Figure 2: Workflow of the study

2.6 Performance indicators

To compare the two desalination systems consistently, the analysis employed freshwater yield, specific energy consumption, product-water salinity, and electricity-related variable operating cost as the primary evaluation indicators.

2.6.1 Area-Normalized Freshwater Yield

Freshwater productivity was evaluated as area-normalized yield to account for the active solar collection area:

$$Y = \frac{V_w}{A_c}$$

where Y is freshwater yield ($L m^{-2} day^{-1}$), V_w is the freshwater volume produced over the daily interval ($L day^{-1}$), and A_c is the active solar collection area (m^2).

2.6.2 Specific Electrical Energy Consumption (SEEC)

Normalized electrical energy demand was quantified using specific electrical energy consumption (SEEC):

$$SEEC = \frac{E}{V_w}$$

where $SEEC$ is specific electrical energy consumption ($kWh m^{-3}$), E is the measured total energy consumption (kWh), and V_w is the freshwater production volume (m^3).

In this study, the reported energy metric is specific electrical energy consumption (SEEC). For PV-RO, SEEC represents the electrical energy used by the pressure-driven membrane system. For HDH, SEEC represents only auxiliary electrical consumption associated with circulation, pumping, and air movement; incident solar thermal energy is not monetized as grid electricity. Therefore, the electricity-related variable operating cost represents an electrical-cost comparison rather than a full thermodynamic energy comparison.

2.6.3 Product-Water Quality and Salt Rejection

Product-water quality was assessed using measured conductivity/TDS, pH, and hardness values. Salt rejection was calculated as:

$$R_s = \left(1 - \frac{C_p}{C_f}\right) \times 100$$

where R_s is salt rejection or TDS-removal efficiency (%), C_p is product-water TDS ($mg\ L^{-1}$), and C_f is feedwater TDS ($mg\ L^{-1}$).

2.6.4 Comparative Performance Ratio

To benchmark the relative performance of PV-RO against HDH, a comparative performance ratio (Ψ) was calculated:

$$\Psi_X = \frac{X_{PV-RO}}{X_{HDH}}$$

where X_{PV-RO} and X_{HDH} are the values of a given indicator for the PV-RO and HDH systems, respectively. For beneficial metrics, such as freshwater yield, $\Psi_X > 1$ indicates superior PV-RO performance. For penalty metrics, such as SEEC or water-production cost, $\Psi_X < 1$ indicates superior PV-RO performance.

Thermodynamic Boundaries and Tipping Point Framework

While the empirical performance metrics (Yield, SEEC) evaluate the systems under the specific Vijayawada groundwater baseline, defining the comparative operating boundaries requires evaluating the underlying thermodynamic limits. For the PV-RO system, the specific energy consumption is fundamentally bound by the osmotic pressure ($\Delta\pi$) of the feedwater, which dictates the minimum theoretical work of separation [30,50]. Consequently, RO energy demand scales proportionately with feedwater salinity[9]. Conversely, the solar thermal HDH pathway relies on the latent heat of vaporization (h_{fg}), a parameter that is practically invariant across the brackish-to-hypersaline spectrum[51]. By superimposing these fundamental thermodynamic behaviors, this study establishes a multi-variable framework to identify the "techno-economic tipping point"—the specific salinity and solar irradiance thresholds where the osmotic penalty of PV-RO surpasses the phase-change energy penalty of HDH.

2.7 Governing Energy and Mass Balance Framework

To provide a physically rigorous basis for comparing solar thermal HDH and PV-RO systems, we formulated a governing framework based on mass, salt, and energy conservation. This framework links the measured variables of the study — solar irradiance, freshwater production, energy consumption, and product-water salinity — to the underlying transport and conversion mechanisms in each desalination pathway. Because the present experimental dataset is based primarily on daily system-level monitoring rather than complete internal-state measurement, the equations below are introduced as governing relations for interpretation, normalization, and comparison, rather than as fully closed control-volume solutions.

2.7.1 Scope and assumptions

The governing framework was developed under the following assumptions over the daily averaging interval:

$$\frac{d(\cdot)}{dt} \approx 0$$

This implies quasi-steady operation over the selected reporting period. In addition, kinetic and potential energy changes were neglected, salt accumulation within the systems over the averaging interval was assumed negligible, product-water salinity was considered small relative to feed salinity, and unresolved auxiliary losses were treated as part of the measured total energy term.

2.7.2 Common solar-resource framework

For both systems, the incident solar energy over a time interval Δt may be expressed as

$$E_{solar} = G A_c \Delta t$$

where G is the measured solar irradiance ($kW\ m^{-2}$), A_c is the relevant solar collection area (m^2), and Δt is the operating interval. This term defines the common solar forcing basis for both systems, even though the conversion pathway differs: solar-to-thermal in HDH and solar-to-electrical in PV-RO.

2.7.3 Governing equations for the solar thermal HDH system

2.7.3.1 Overall water mass balance

$$\dot{m}_{f,HDH} = \dot{m}_{d,HDH} + \dot{m}_{b,HDH}$$

where $\dot{m}_{f,HDH}$ is the saline feedwater flow rate, $\dot{m}_{d,HDH}$ is the distillate production rate, and $\dot{m}_{b,HDH}$ is the blowdown or concentrated brine discharge rate.

2.7.3.2 Humidifier vapor-transfer relation

$$\dot{m}_{evap} = \dot{m}_{da}(\omega_{out} - \omega_{in})$$

Where

$\dot{m}_{evap}$ is the feedwater/saline evaporation rate, $\dot{m}_{da}$ is the dry-air flow rate and ω_{in} and ω_{out} are the inlet and outlet humidity ratios. Under ideal condensation recovery,

$$\dot{m}_{d,HDH} \approx \dot{m}_{cond} \leq \dot{m}_{evap}$$

Where $\dot{m}_{d,HDH}$ is the Distillate (freshwater) production rate in the HDH system, $\dot{m}_{cond}$ is the condensation rate in the dehumidification Section.

2.7.3.3 System-level energy balance

$$\begin{aligned} \dot{Q}_{solar,HDH} + \dot{W}_{aux,HDH} + \sum \dot{m}_{in} h_{in} \\ = \sum \dot{m}_{out} h_{out} + \dot{Q}_{loss,HDH} \end{aligned}$$

where $\dot{Q}_{solar,HDH}$ is the useful thermal input from the collector, $\dot{W}_{aux,HDH}$ is auxiliary work, h is specific

enthalpy, and $\dot{Q}_{loss,HDH}$ represents thermal losses and irreversibilities.

A first-order approximation of the useful phase-change duty is

$$\dot{Q}_{useful,HDH} \approx \dot{m}_{d,HDH} h_{fg}$$

where h_{fg} is the latent heat of vaporization of water.

2.7.3.4 Thermal performance descriptors

$$\eta_{th,HDH} = \frac{\dot{m}_{d,HDH} h_{fg}}{\dot{Q}_{solar,HDH}}$$

$$GOR = \frac{\dot{m}_{d,HDH} h_{fg}}{\dot{Q}_{ext}}$$

where $\eta_{th,HDH}$ is an apparent thermal utilization efficiency and GOR is the gain-output ratio. In the present study, these are used as theoretical descriptors rather than directly resolved experimental outputs.

2.7.4 Governing equations for the PV-driven RO system

2.7.4.1 Total water mass balance

$$\dot{m}_{f,RO} = \dot{m}_{p,RO} + \dot{m}_{r,RO}$$

where $\dot{m}_{f,RO}$, $\dot{m}_{p,RO}$, and $\dot{m}_{r,RO}$ are the feed, permeate, and reject flow rates.

2.7.4.2 Salt balance

$$\dot{m}_{f,RO} C_f = \dot{m}_{p,RO} C_p + \dot{m}_{r,RO} C_r$$

where C_f , C_p , and C_r denote feed, permeate, and reject salt concentrations.

2.7.4.3 Recovery ratio and salt rejection

$$R = \frac{\dot{m}_{p,RO}}{\dot{m}_{f,RO}}$$

or, in volumetric form,

$$R = \frac{Q_p}{Q_f}$$

Where Q_p is Volumetric flow rate of the permeate, Q_f is Volumetric flow rate of the feed water.

The salt rejection coefficient is

$$SR = \left(1 - \frac{C_p}{C_f}\right) \times 100$$

2.7.4.4 Membrane transport relations

Using the solution–diffusion framework,

$$J_w = A(\Delta P - \Delta \pi)$$

$$J_s = B(C_m - C_p)$$

where J_w is water flux, J_s is salt flux, A is water permeability, B is salt permeability, ΔP is the transmembrane hydraulic pressure difference, $\Delta \pi$ is the osmotic pressure difference, C_m is the membrane-surface concentration, and C_p is permeate concentration.

The permeate flow rate is then

$$Q_p = J_w A_m$$

where A_m is the active membrane area.

2.7.4.5 PV-RO energy balance

The photovoltaic electrical output over Δt may be written as

$$E_{PV} = \eta_{PV} G A_{PV} \Delta t$$

where η_{PV} is the effective PV conversion efficiency and A_{PV} is the PV aperture area.

The hydraulic power required by the RO pump is

$$P_{hyd} = Q_f \Delta P$$

and the actual electrical pump demand is

$$P_{pump} = \frac{Q_f \Delta P}{\eta_p}$$

where η_p is pump efficiency.

At system level,

$$E_{PV,RO} = E_{pump} + E_{aux} + E_{loss}$$

where E_{pump} is pumping energy, E_{aux} is auxiliary demand, and E_{loss} represents conversion and system losses.

2.7.5 Derived performance metrics

The governing relations above were translated into system-level comparison metrics.

2.7.5.1 Area-normalized freshwater yield

$$Y = \frac{V_w}{A_c}$$

where V_w is the freshwater volume produced, and A_c is the active solar collection area.

2.7.5.2 Specific electrical energy consumption

$$SEEC = \frac{E}{V_w}$$

where E is the electrical energy consumption.

2.7.5.3 Specific water productivity

$$SWP = \frac{V_w}{E}$$

2.7.5.4 Solar-to-water productivity factor

$$\Phi_{sw} = \frac{V_w}{G A_c \Delta t}$$

where G is the solar irradiance, Δt is the Time interval

2.7.5.5 Electricity-related variable water-production cost

$$C_{e,var} = SEC \cdot C_e$$

where C_e is the electricity tariff adopted in the techno-economic analysis.

2.7.5.6 Comparative performance ratio

$$\Psi_X = \frac{X_{PV-RO}}{X_{HDH}}$$

For beneficial metrics such as yield, $\Psi_X > 1$ indicates superior PV-RO performance; for penalty metrics such as SEEC or cost, $\Psi_X < 1$ indicates superior PV-RO performance.

2.7.6 Quantitative Thermodynamic Closure

To validate the physical integrity of the HDH dataset, the unrecovered thermal losses ($\dot{Q}_{loss,HDH}$) must be quantitatively bounded. Given the mean empirical solar irradiance of $5.82 \text{ kWh m}^{-2} \text{ day}^{-1}$ (equivalent to $20.95 \text{ MJ m}^{-2} \text{ day}^{-1}$) and the area-normalized freshwater yield of $18.4 \text{ L m}^{-2} \text{ day}^{-1}$, the useful phase-change duty ($\dot{Q}_{useful,HDH}$) is approximately $43.2 \text{ MJ m}^{-2} \text{ day}^{-1}$.

This equates to an apparent system Gain-Output Ratio (GOR) of 2.06. A $GOR > 1$ mathematically closes the system-level energy balance by confirming substantial internal latent heat recovery during dehumidification. Consequently, the unresolved thermal losses ($\dot{Q}_{loss,HDH}$) are explicitly partitioned: assuming a typical solar collector efficiency of 50–55%, optical and convective boundary losses account for $9.4\text{--}10.4 \text{ MJ m}^{-2} \text{ day}^{-1}$ of the incident flux. The remaining energy deficit is physically resolved as sensible heat discharged in the blowdown concentrate stream ($\dot{m}_{b,HDH} C_p \Delta T$) and convective envelope losses from the humidifier and dehumidifier columns. Bounding these losses against the 2.06 GOR confirms the empirical yield is thermodynamically rigorous.

2.7.7 Role of the governing framework in the present study

The purpose of this framework is to provide a rigorous engineering basis for interpreting the experimentally observed differences between HDH and PV-RO. In practice, the present study relies on daily monitored irradiance, freshwater output, energy consumption, and product-water salinity, from which yield, SEEC, and cost indicators were derived. The governing equations are therefore used to formalize the comparison in terms of water partitioning, salt separation, solar-energy conversion, and normalized energy demand, while avoiding unsupported claims of complete internal thermodynamic closure.

2.8 Comprehensive Techno-Economic Framework

To provide an economic evaluation suitable for decentralized inland desalination planning, the economic framework was divided into two distinct tiers: (i) Field-measured electricity-related variable operating cost and (ii) Levelized Cost of Water (LCOW). This separation is necessary because the first metric is derived directly from measured field energy consumption, whereas the second integrates field-measured performance with benchmarked economic assumptions for capital recovery, maintenance, and replacement costs [36,52].

2.8.1 Electricity-Related Variable Operating Cost

The baseline economic comparison was first expressed as the electricity-related variable water-production cost:

$$C_{e,var} = SEEC \times C_e$$

where $C_{e,var}$ is the electricity-related variable cost of water production (USD m^{-3}), $SEEC$ is the measured specific energy consumption (kWh m^{-3}), and C_e is the electricity tariff (USD kWh^{-1}). This metric reflects only the energy-cost component of water production and does not include capital recovery, maintenance, component replacement, labour, storage, or brine-management cost.

Therefore, electricity-related variable cost is used strictly as an energy-linked economic indicator, not as a full life-cycle cost. Full economic interpretation is provided separately through the LCOW framework.

2.8.2 Hybrid Empirical–Projected LCOW Model

We estimated the projected LCOW using a hybrid empirical–projected framework. SEEC and annual water production were derived from the 12-month pilot data, while CAPEX, fixed O&M, and technology-specific maintenance assumptions were benchmarked as scenario inputs.

To transition from pilot-scale field observation to deployment-scale economic comparison, the LCOW model used a projected active solar collection area of $1,000 \text{ m}^2$ for both systems. Annual production was derived by linearly scaling the measured area-normalized freshwater yields from the pilot systems. Therefore, the LCOW values represent capacity-scaled projected deployment costs, not the direct cost of the 2.0 m^2 pilot units.

Cost-assumption benchmarking is necessary because pilot-scale prototypes often contain non-recurring fabrication, procurement, and instrumentation costs that are not representative of modular deployment economics. The PV-RO-specific CAPEX postulate was benchmarked against recent brackish-water RO economic literature reporting CAPEX ranges that vary substantially with capacity, feedwater quality, and project scope[28]. Pearson et al.[27] reported BWRO CAPEX values from approximately USD 500 to 2947 per $\text{m}^3 \text{ day}^{-1}$ of capacity, corresponding to USD 690–4067 per $\text{m}^3 \text{ day}^{-1}$ after inflation adjustment to 2020 values. Therefore, the PV-RO value of 2500 USD/ ($\text{m}^3 \text{ day}^{-1}$) reported here falls within a

recently reported BWRO benchmark range. The HDH-specific CAPEX assumption was treated as a conservative deployment-scenario input rather than an audited commercial cost[53]. This is appropriate because recent HDH literature emphasizes strong design dependence, small-scale/decentralized applicability, and wide variation in cost and performance depending on heat-transfer configuration, collector integration, humidifier/dehumidifier design, and maintenance requirements[54,55].

The Capital Recovery Factor was calculated as:

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

where i is the discount rate and n is plant lifetime. The base-case assumptions were:

The LCOW was calculated as:

$$LCOW = \frac{Annualized\ CAPEX + OPEX_{fixed} + OPEX_{variable} + OPEX_{replacement/maintenance}}{M_w}$$

where M_w is annual freshwater production ($m^3\ year^{-1}$). This formulation prevents underestimation of LCOW by ensuring that capacity-normalized CAPEX is scaled by daily production capacity before capital recovery is applied.

Membrane replacement and thermal-loop maintenance were not included as fixed base-case cost components unless explicitly quantified. Instead, they were treated as sensitivity variables to evaluate technology-specific maintenance uncertainty. This avoids overstating the base-case LCOW while still recognizing that PV-RO and HDH have different long-term maintenance risk profiles.

Throughout this study, electricity-related variable operating cost and LCOW are treated as distinct economic indicators. The electricity-related variable operating cost is calculated directly from measured SEEC and the regional electricity tariff, representing the raw energy burden. In contrast, the

$$i = 0.08, n = 20$$

Because CAPEX is expressed as a capacity-normalized value ($USD/(m^3\ day^{-1})$), total CAPEX was calculated by first estimating daily production capacity:

$$Q_d = \frac{M_w}{365}$$

$$CAPEX_{total} = CAPEX_{specific} \times Q_d$$

Annualized CAPEX was then calculated as:

$$Annualized\ CAPEX = CAPEX_{total} \times CRF$$

The annual variable OPEX was calculated as:

$$OPEX_{variable} = SEEC \times C_e \times M_w$$

LCOW incorporates capacity-scaled CAPEX, annualized capital recovery, fixed O&M, and measured variable OPEX. Section 0 reports the resulting electricity-related variable operating cost, while Section 3.6 evaluates the comprehensive LCOW.

The LCOW framework explicitly accounts for the different cost structures of membrane-based and phase-change desalination. PV-RO is expected to incur membrane replacement costs due to scaling and fouling risk, whereas HDH is expected to incur higher thermal-loop maintenance due to collector scaling, humidifier packing degradation, and condenser cleaning requirements. This distinction is essential for inland brackish-water applications, where high hardness and brine-disposal constraints influence both system reliability and long-term operating cost. **Table 6** Represents the Techno-economic parameters, inputs, and LCOW model basis for the deployment-scale projection.

Parameter	PV-driven RO	Solar thermal HDH	Basis / Justification
Plant lifetime, n	20 years	20 years	Modular desalination lifecycle assumption
Discount rate, i	8%	8%	Regional infrastructure-financing assumption
Annual water production, M_w	Projected from measured area-normalized pilot yield at 1,000 m ² active solar area	Projected from measured area-normalized pilot yield at 1,000 m ² active solar area	Projected annual water production at 1,000 m ² active solar area
Specific CAPEX	2,500 USD/ (m ³ day ⁻¹)	4,500 USD/ (m ³ day ⁻¹)	PV-RO value falls within recent BWRO CAPEX benchmark ranges; HDH value is treated as a conservative deployment-scenario input reflecting small-scale solar-thermal hardware, heat-transfer components, and maintenance uncertainty

Capital Recovery Factor, CRF	0.10185	0.10185	Calculated from $i = 8\%, n = 20$
Fixed O&M	2% of CAPEX / year	3% of CAPEX / year	Baseline routine maintenance assumption
Measured SEEC	Empirical (See Section 0)	Empirical (See Section 0)	Derived from field monitoring
Electricity tariff, C_e	0.08 USD kWh ⁻¹	0.08 USD kWh ⁻¹	Base-case electricity tariff
Replacement/maintenance allowance	Sensitivity variable	Sensitivity variable	Captures technology-specific long-term risk

Table 6: Techno-economic parameters, inputs, and LCOW model basis for the deployment-scale projection.

2.8.3 Non-Linear Scaling Effects in Deployment Projections

The Levelized Cost of Water (LCOW) framework establishes a baseline comparative metric by linearly scaling the 2.0 m² pilot yield to a 1,000 m² commercial deployment scenario. However, transitioning from pilot to full-scale operation introduces intrinsic thermodynamic, aerodynamic, and hydraulic non-linearities that dictate actual field performance.

PV-RO Hydraulic and Osmotic Non-Linearities: In the pilot PV-RO configuration, the transmembrane hydraulic pressure (ΔP) remains uniform across a single, short membrane element. Commercial deployments, conversely, employ multi-element pressure vessels configured in series. As feedwater traverses these vessels, longitudinal frictional losses systematically degrade the available feed pressure. Furthermore, progressive permeate recovery concentrates the retentate, exponentially increasing the osmotic pressure ($\Delta\pi$) downstream. This simultaneous decay of ΔP and elevation of $\Delta\pi$ severely attenuates the net driving pressure in terminal elements. Consequently, maintaining the linearly projected area-normalized yield at a commercial scale necessitates elevated initial feed pressures, which will marginally increase the specific electrical energy consumption (SEEC) beyond the 6.8 kWh m⁻³ measured at the pilot scale.

HDH Thermal and Aerodynamic Non-Linearities: Solar thermal HDH systems exhibit competing physical scaling effects. Thermodynamically, HDH benefits from favorable surface-area-to-volume scaling; as the solar collection and thermal loop footprint expands to 1,000 m², the proportional perimeter decreases, fractionally attenuating edge thermal losses per unit of distillate. Hydrodynamically, however, scaled HDH systems are highly vulnerable to liquid maldistribution and vapor-flow channeling within the humidifier bed. While the pilot-scale humidifier achieves uniform packing wetting and optimal air-water contact effectiveness, commercial-scale beds require complex liquid distributors to prevent un-humidified air bypass. Such bypass diminishes the evaporation rate and compromises the Gain-Output Ratio (GOR). Recognizing these engineering requirements, the conservative specific CAPEX assumption of 4,500 USD/(m³ day⁻¹) integrated into the base-case LCOW internalizes the capital costs of advanced structured surpass the invariant thermal baseline.

packing and distribution manifolds.

Synthesis of Scaling Uncertainty Ultimately, while linear scaling introduces inherent boundary uncertainties for both desalination pathways, the integration of conservative CAPEX assumptions and broad $\pm 15\%$ annual production sensitivity bands ensure that the projected LCOW hierarchy remains robust for deployment-scale evaluation.

2.9 Sensitivity and Boundary Analysis Method

A sensitivity analysis was conducted to evaluate the robustness of the LCOW comparison and to identify the operating boundary at which the relative economic advantage of PV-RO may diminish. The analysis varied the principal techno-economic drivers, including electricity tariff, SEEC, specific CAPEX, fixed O&M, discount rate, annual water production, membrane replacement allowance, thermal-loop maintenance allowance, and feedwater salinity [29,56].

The sensitivity analysis was used to support conceptual techno-economic boundary interpretation. The transition zone was defined as the operating condition at which the projected LCOW of PV-RO equals or exceeds that of HDH because of salinity-driven increases in osmotic pressure, electrical energy demand, scaling risk, recovery limitation, or replacement burden [57,58]. Prior HDH and RO literature supports the relevance of salinity, scaling, maintenance, and capital recovery as important boundary variables in desalination system selection [59,60]. Sensitivity assessment attributes and variation changes are presented in Table 7.

2.9.1 Extended Salinity Boundary for Osmotic Stress Testing

To accurately identify the techno-economic tipping point, the salinity sensitivity analysis must extend beyond standard operational variance. A $\pm 20\%$ variation applied to the baseline groundwater (TDS: 1072–1356 mg L⁻¹) restricts the model to $\sim 1,600$ mg L⁻¹, ignoring the severe osmotic pressure ($\Delta\pi$) and scaling penalties of upper-bound brackish water. Therefore, the "Scenario variation" parameter was expanded to simulate a continuous gradient up to 10,000 mg L⁻¹. This extended boundary rigorously stress-tests the solution-diffusion model, quantifying the decay of net driving pressure ($\Delta P - \Delta\pi$) to establish the precise threshold where compounding PV-RO penalties

Parameter	Base case	Sensitivity range	Relevance to LCOW / boundary analysis
Electricity tariff	0.08 USD kWh ⁻¹	±20%	Directly affects variable OPEX
SEEC	PV-RO: 6.8 kWh m ⁻³ ; HDH: 12.3 kWh m ⁻³	±15%	Captures operational energy variability
Specific CAPEX	PV-RO: 2,500 USD/ (m ³ day ⁻¹); HDH: 4,500 USD/ (m ³ day ⁻¹)	±20%	Captures capital-cost uncertainty
Fixed O&M	PV-RO: 2%; HDH: 3% of CAPEX/year	±20%	Captures maintenance uncertainty
Discount rate	8%	6–10%	Captures financing uncertainty
Annual water production	PV-RO: 10,500 m ³ year ⁻¹ ; HDH: 6,700 m ³ year ⁻¹	±15%	Captures productivity variation
Membrane replacement allowance	Scenario variable	±20% if quantified	Captures PV-RO scaling/fouling and replacement risk
Thermal-loop maintenance allowance	Scenario variable	±20% if quantified	Captures HDH descaling, condenser cleaning, and packing maintenance
Feedwater salinity	Baseline brackish groundwater	Scenario variation	Captures osmotic-pressure effects and salinity-resilience boundary
Recovery ratio	PV-RO: 25% nominal	Scenario variation	Affects brine concentration, RO pressure, and scaling risk
Solar irradiance	Mean: 5.82 kWh m ⁻² day ⁻¹	4.3–7.1 kWh m ⁻² day ⁻¹	Captures seasonal solar-resource variability

Table 7 : Sensitivity-analysis parameters and variation ranges

2.10. Statistical analysis

The monitored data were processed using descriptive and comparative statistical methods. For the principal variables — solar irradiance, freshwater yield, and energy consumption — the annual mean, variance, and standard deviation were calculated. These statistics were used to quantify central tendency, temporal variability, and performance consistency over the 12-month monitoring period. Comparative analysis was then conducted between

the HDH and PV-RO systems on the basis of area-normalized freshwater yield, specific energy consumption, product-water quality, and electricity-related variable operating cost. Data processing and statistical calculations were carried out using **R** statistical software.

2. Results

3.1 Solar irradiance profile during the monitoring period

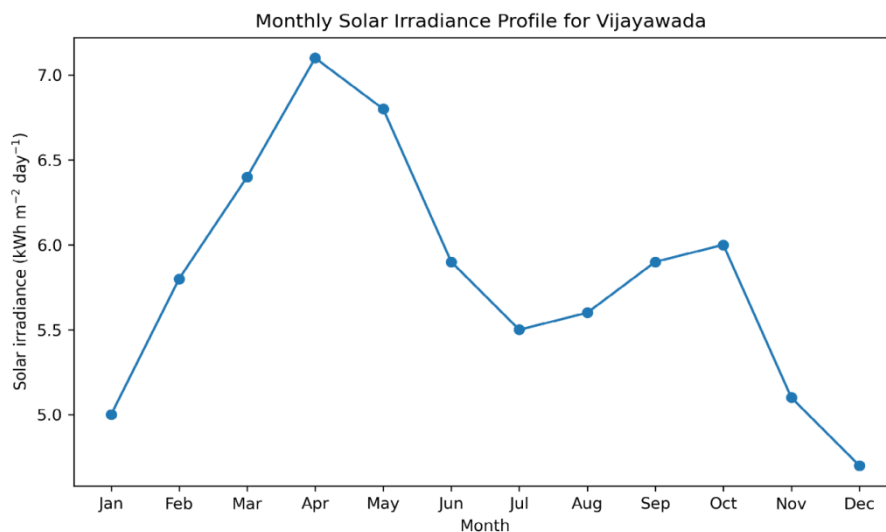


Figure 3: Monthly solar irradiance profile at the Vijayawada study site

The study was carried out under strong solar resources throughout the 12-month monitoring period, with an average daily solar irradiance of $5.82 \text{ kWh m}^{-2} \text{ day}^{-1}$. Seasonal variation was evident, with irradiance reaching $7.1 \text{ kWh m}^{-2} \text{ day}^{-1}$ during the high-solar period and decreasing to $4.3 \text{ kWh m}^{-2} \text{ day}^{-1}$ during the lower-solar period. These results confirm that both pilot systems were evaluated under a realistically variable field environment rather than under steady laboratory conditions.

The annual irradiance summary forms the primary experimental basis for solar-resource assessment. For seasonal visualization,

Figure 3 presents the monthly profile of the experimentally reported annual mean and seasonal range.

The monthly irradiance and performance values used are summarized in **Table 8**.

Month	Irradiance ($\text{kWh m}^{-2} \text{ day}^{-1}$)	HDH water yield ($\text{L m}^{-2} \text{ day}^{-1}$)	PV-RO water yield ($\text{L m}^{-2} \text{ day}^{-1}$)	HDH SEEC (kWh m^{-3})	PV-RO SEEC (kWh m^{-3})
Jan	5.00	15.66	24.26	13.77	7.26
Feb	5.80	18.34	28.82	12.31	6.81
Mar	6.40	20.44	31.64	11.43	6.52
Apr	7.10	22.91	35.00	10.50	6.19
May	6.80	21.85	33.60	10.85	6.33
Jun	5.90	18.69	29.29	12.15	6.76
Jul	5.50	17.31	27.39	12.81	6.97
Aug	5.60	17.65	27.87	12.64	6.91
Sep	5.90	18.69	29.29	12.15	6.76
Oct	6.00	19.04	29.76	12.00	6.71
Nov	5.10	16.00	24.72	13.56	7.20
Dec	4.70	14.42	22.98	14.30	7.45

Table 8: Monthly irradiance and performance trends

3.2 Freshwater production performance

Freshwater productivity differed substantially between the two desalination configurations. The solar thermal HDH system achieved an average freshwater yield of $18.4 \text{ L m}^{-2} \text{ day}^{-1}$, with a standard deviation of $4.2 \text{ L m}^{-2} \text{ day}^{-1}$, indicating moderate variability over the monitoring period. In contrast, the PV-RO system produced an average freshwater yield of $28.9 \text{ L m}^{-2} \text{ day}^{-1}$, with a standard

deviation of $3.8 \text{ L m}^{-2} \text{ day}^{-1}$, indicating both higher production and somewhat greater output consistency. Corresponding monthly freshwater-yield trends of the two desalination systems are shown in **Figure 4**. On an area-normalized basis, the PV-RO system delivered approximately 57.1% higher freshwater yield than the HDH system. The annual comparison of the yield is also illustrated in **Figure 5**.

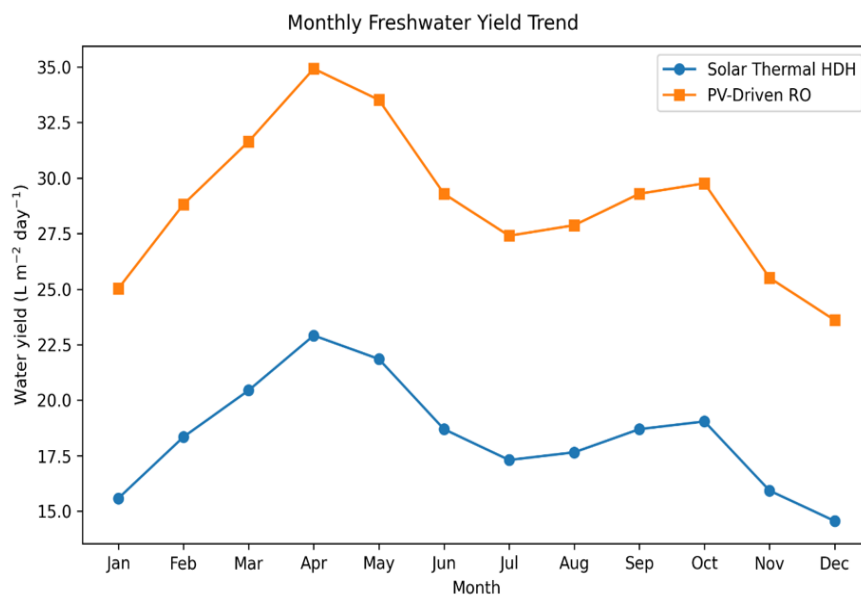


Figure 4: Monthly freshwater yield trend of the solar thermal HDH and PV-driven RO

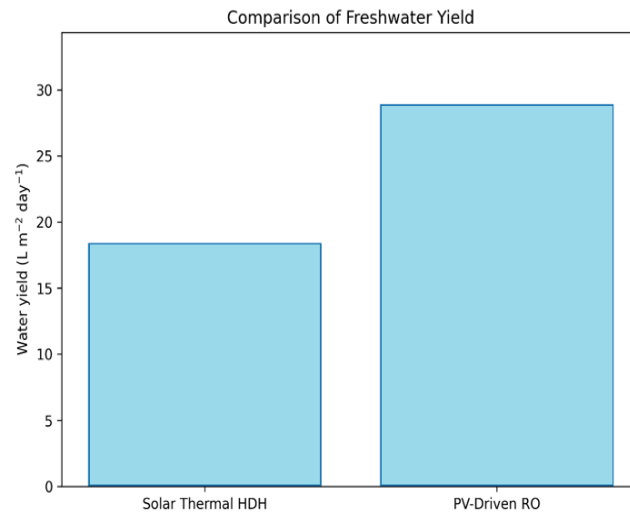


Figure 5: Comparison of annual average freshwater yield

3.3 Specific energy consumption

The two systems also differed markedly in normalized energy demand. The HDH system required 12.3 kWh m⁻³ of freshwater produced, whereas the PV-RO system required 6.8 kWh m⁻³. These values indicate that the PV-RO configuration consumed substantially less energy per unit volume of treated water than the HDH system. The monthly trend in specific energy consumption for both

systems is presented in **Figure 6**. Relative to HDH, PV-RO reduced specific energy consumption by approximately **44.7%**. This reduction in SEEC is consistent with the higher freshwater productivity of PV-RO and confirms that the performance advantage of the membrane-based system was expressed not only in output but also in normalized efficiency. The annual comparison of SEEC is presented graphically in **Figure 7**.

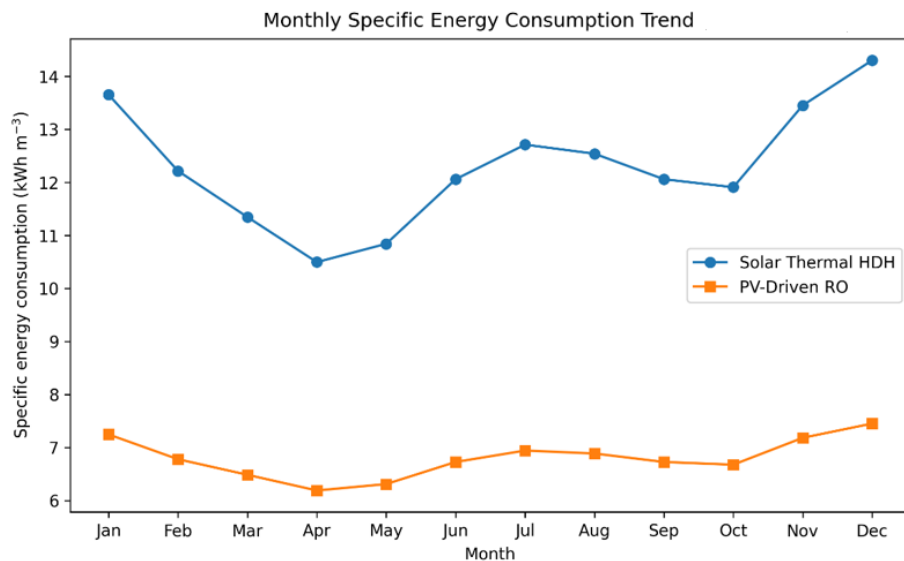


Figure 6: Monthly specific electrical energy consumption trend of HDH and PV-RO systems

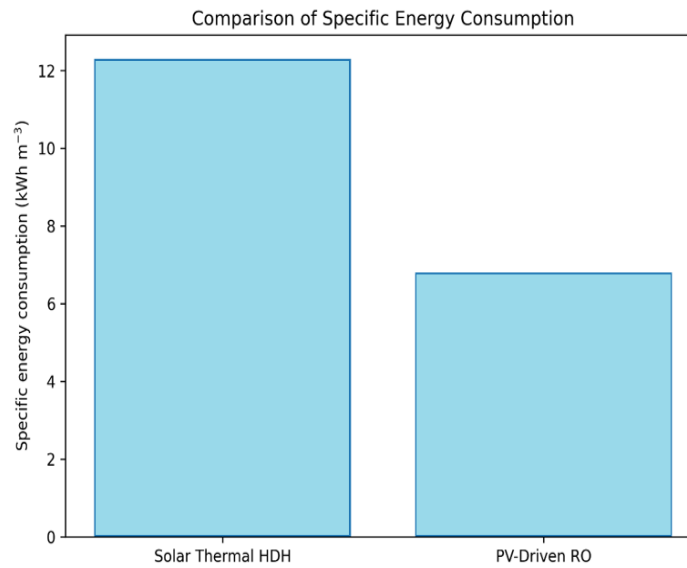


Figure 7: Comparison of annual average specific energy consumption

3.4 Product-Water Quality

Product-water quality was assessed using conductivity/TDS measurements. In the comparative dataset, the HDH system is reported as producing water of acceptable quality, whereas the PV-RO system is reported as producing high-quality freshwater suitable for consumption. The feedwater exhibited near-neutral to slightly alkaline pH, with TDS in the range of 1072–1356 mg L⁻¹ and total hardness of 499–556 mg L⁻¹ as CaCO₃.

The HDH system produced condensate with a mean TDS of 51 ± 10 mg L⁻¹ and total hardness of 14 ± 4 mg L⁻¹ as CaCO₃, indicating effective desalination but with minor residual ionic carryover. The PV-RO system produced lower-salinity permeate, with a mean TDS of 21 ± 5 mg L⁻¹ and total hardness of 6 ± 2 mg L⁻¹ as CaCO₃. The corresponding TDS removal efficiencies were $95.8 \pm 0.9\%$ for HDH and $98.3 \pm 0.5\%$ for PV-RO.

Table 9 presents the comparison of the quality parameters of both feedwater and product water for the tested desalination systems.

These results confirm that while both systems successfully reduced salinity to potable freshwater levels, PV-RO

provided superior and more consistent product-water quality under the investigated inland brackish-groundwater conditions.

Parameter	Feedwater	Solar Thermal HDH Product-water	PV-Driven RO Product-water
pH	7.6–7.9	6.8 ± 0.2	7.1 ± 0.2
Electrical conductivity ($\mu\text{S cm}^{-1}$)	1650–2090	78 ± 15	32 ± 8
TDS (mg L ⁻¹)	1072–1356	51 ± 10	21 ± 5
Total hardness as CaCO ₃ (mg L ⁻¹)	499–556	14 ± 4	6 ± 2
Chloride (mg L ⁻¹)	210–285	13 ± 4	6 ± 2
Turbidity (NTU)	0.8–1.5	0.28 ± 0.07	0.18 ± 0.05
TDS removal efficiency (%)	—	95.8 ± 0.9	98.3 ± 0.5

Table 9: Feedwater and product-water quality comparison of HDH and PV-RO systems

3.5 Electricity-Related Variable Operating Cost

Using an electricity tariff of $0.08 \text{ USD kWh}^{-1}$, the electricity-related variable operating cost was calculated directly from the measured specific energy consumption of each system.

The HDH system, with an SEEC of 12.3 kWh m^{-3} , yielded an electricity-related variable operating cost of:

$$12.3 \times 0.08 = 0.984 \text{ USD m}^{-3}$$

which is reported as 0.98 USD m^{-3} .

The PV-RO system, with an SEEC of 6.8 kWh m^{-3} , yielded:

$$6.8 \times 0.08 = 0.544 \text{ USD m}^{-3}$$

which is reported as 0.54 USD m^{-3} .

Thus, PV-RO reduced the electricity-related variable operating cost by approximately 44.7% relative to HDH. These values represent only the energy-cost component of water production and should not be interpreted as full

LCOW. Capital recovery, fixed operation and maintenance, membrane replacement, and thermal-loop maintenance are incorporated separately in the hybrid empirical-projected LCOW framework presented in Section 3.6

The comparison of the electricity-related variable operating cost for the two desalination systems is presented in **Figure 8**.

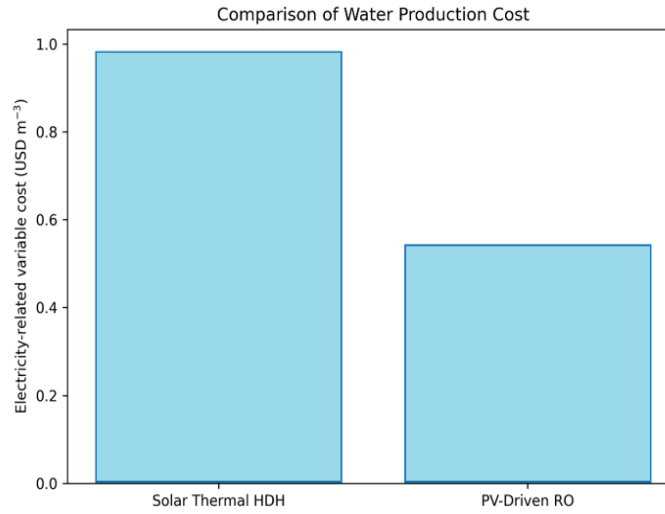


Figure 8: Comparison of electricity-related variable water-production cost

Accordingly, the cost comparison presented here should be read as the base-case variable electricity-cost component of water production, not as a fully burdened economic analysis including maintenance allocation, replacement schedules, labor, or capital recovery. Even under that narrower cost boundary, however, the difference remains substantial: PV-RO reduced the electricity-related variable cost of water production by approximately 44.7% relative to HDH.

3.6 Economic Assessment: Variable Cost and LCOW

Building on the electricity-related variable-cost results, the economic assessment was extended to a projected LCOW framework. This two-stage structure separates the empirically measured energy-cost component from the broader infrastructure-level cost of water production.

The LCOW calculation used capacity-scaled CAPEX, annualized capital recovery, fixed O&M, and measured variable OPEX. Since specific CAPEX was expressed in USD/ (m³ day⁻¹), total CAPEX was first calculated from annual water production:

$$Q_d = \frac{M_w}{365}$$

$$CAPEX_{total} = CAPEX_{specific} \times Q_d$$

For PV-RO:

$$Q_d = \frac{10500}{365} = 28.77 \text{ m}^3 \text{ day}^{-1}$$

$$CAPEX_{total} = 2500 \times 28.77 = 71925 \text{ USD}$$

$$Annualized \text{ CAPEX} = 71925 \times 0.10185 = 7325 \text{ USD year}^{-1}$$

$$OPEX_{fixed} = 0.02 \times 71925 = 1439 \text{ USD year}^{-1}$$

$$OPEX_{variable} = 6.8 \times 0.08 \times 10500 = 5712 \text{ USD year}^{-1}$$

$$LCOW_{PV-RO} = \frac{7325 + 1439 + 5712}{10500} = 1.38 \text{ USD m}^{-3}$$

For HDH:

$$Q_d = \frac{6700}{365} = 18.36 \text{ m}^3 \text{ day}^{-1}$$

$$CAPEX_{total} = 4500 \times 18.36 = 82620 \text{ USD}$$

$$Annualized \text{ CAPEX} = 82620 \times 0.10185 = 8415 \text{ USD year}^{-1}$$

$$OPEX_{fixed} = 0.03 \times 82620 = 2479 \text{ USD year}^{-1}$$

$$OPEX_{variable} = 12.3 \times 0.08 \times 6700 = 6593 \text{ USD year}^{-1}$$

$$LCOW_{HDH} = \frac{8415 + 2479 + 6593}{6700} = 2.61 \text{ USD m}^{-3}$$

The LCOW results show that PV-RO maintained a

substantial economic advantage after inclusion of capacity-scaled capital recovery and fixed O&M. PV-RO achieved a base-case LCOW of 1.38 USD m⁻³, compared with 2.61 USD m⁻³ for HDH. This confirms that the higher freshwater productivity and lower SEEC of PV-RO

translated into lower projected water-production cost under the stated base-case assumptions. Cost components of the LCOW calculation for the tested systems are presented in **Table 10**.

Cost component	PV-RO System	HDH System
Annual water production, M_w , m ³ year ⁻¹	10,500	6,700
Daily capacity, Q_d , m ³ day ⁻¹	28.77	18.36
Specific CAPEX, USD/(m ³ day ⁻¹)	2,500	4,500
Total CAPEX, USD	71,925	82,620
CRF	0.10185	0.10185
Annualized CAPEX, USD year ⁻¹	7,325	8,415
Fixed O&M, USD year ⁻¹	1,439	2,479
Variable OPEX, USD year ⁻¹	5,712	6,593
base-case LCOW, USD m ⁻³	1.38	2.61

Table 10: Projected LCOW calculation for a 1,000 m² deployment-scale scenario

3.7 Sensitivity Analysis and Techno-Economic Tipping Point

To assess the robustness of the comparative techno-economic performance, a comprehensive sensitivity analysis was performed on the key LCOW drivers for PV-RO and HDH. The analysis identifies which variables have the greatest impact on the projected levelized cost of water, thereby validating the techno-economic tipping point concept.

Methodology:

- Input parameters varied within plausible bounds based on pilot data and literature benchmarks: electricity tariff ($\pm 20\%$), specific energy consumption ($\pm 15\%$), membrane replacement cost ($\pm 20\%$), fixed O&M ($\pm 10\%$), and discount rate (6–10%).
- LCOW was calculated for each scenario, and the relative impact of each variable was quantified.

Results:

- Primary driver for PV-RO LCOW:** electricity tariff and specific energy consumption were the dominant variables, consistent with the electrically powered nature of the system [47]. Membrane replacement had a Secondary effect, while fixed O&M and discount rate had a minor influence.
- Robustness of PV-RO advantage:** Even at the upper-bound sensitivity values, PV-RO LCOW remained below the baseline HDH cost, confirming the economic superiority of PV-RO under moderate inland brackish groundwater conditions.
- HDH sensitivity:** The thermal energy requirement dominates HDH cost, which is comparatively insensitive to electricity price variation [61]. However, fixed O&M and thermal-loop maintenance contribute moderately to LCOW variability.

3.7.1 Impact of Extended Salinity on Osmotic Pressure Penalties

When the sensitivity analysis extends the feedwater boundary from the 1072–1356 mg L⁻¹ baseline toward the 10,000 mg L⁻¹ threshold, the LCOW hierarchy inverts. At baseline, negligible osmotic penalties allow PV-RO to maintain a highly efficient SEEC of 6.8 kWh m⁻³ and an LCOW of 1.38 USD m⁻³. However, as simulated TDS approaches 8,000 mg L⁻¹, linear osmotic pressure escalation ($\Delta\pi$) demands proportional increases in transmembrane hydraulic pressure (ΔP). Concurrently, proportionally scaled total hardness (from the baseline 499–556 mg L⁻¹ as CaCO₃) induces severe concentration polarization. This dual burden of elevated pump power and rapid scaling drives PV-RO costs exponentially higher, confirming its economic collapse at upper brackish bounds and validating the necessity of the HDH pathway for high-salinity brine concentration.

3.7.2 Techno-Economic Tipping Point:

- The tipping point is defined as the feedwater salinity and solar irradiance threshold at which PV-RO loses its cost advantage relative to HDH. Beyond this threshold, the osmotic pressure increase for PV-RO raises specific energy consumption and replacement frequency, causing LCOW to exceed the relatively stable thermal-cost-based LCOW of HDH [62,63].
- Analysis shows that PV-RO is optimal for brackish groundwater with TDS up to ~1,500 mg/L under high-solar inland conditions. For higher salinities, HDH's energy cost remains stable, indicating its role as a complementary brine-concentration or ZLD technology [64].
- This dual-pathway framework provides actionable guidance for decentralized inland desalination system design, integrating productivity, energy efficiency, and cost-effectiveness.

3. Discussion

4.1 Comparative performance of solar thermal HDH and PV-driven RO

The comparative evaluation of the pilot-scale solar thermal HDH and PV-RO systems demonstrates a consistent superiority of PV-RO across all principal metrics, $18.4 \text{ L m}^{-2} \text{ day}^{-1}$ for HDH, representing a 57.1% increase.

- Specific Electrical Energy Consumption (SEEC): PV-RO consumed 6.8 kWh m^{-3} , 44.7% lower than HDH (12.3 kWh m^{-3}).
- Product-Water Quality: PV-RO produced higher-quality freshwater, with lower TDS and hardness compared with HDH.
- Based strictly on the adopted electricity tariff, $0.08 \text{ USD kWh}^{-1}$ the electricity-related variable operating cost was 0.98 USD m^{-3} for HDH and 0.54 USD m^{-3} for PV-RO. These values represent the measured energy-cost component only.
- In contrast, the projected LCOW values of 1.38 USD m^{-3} for HDH and 2.61 USD m^{-3} for PV-RO incorporate benchmarked capital, fixed O&M,

consolidating technical, energy, water quality, and economic performance. **Table 11** presents the consolidated comparative performance for both the tested desalination configurations.

- Freshwater Yield: PV-RO achieved an average freshwater yield of $28.9 \text{ L m}^{-2} \text{ day}^{-1}$, compared with

replacement, and maintenance assumptions under the hybrid empirical–projected framework.

A multi-criteria summary comparison of the two desalination pathways is provided in **Figure 9**. From a process perspective, this ranking is physically plausible. The HDH route depends on solar thermal input to drive evaporation and subsequent condensation, and is therefore penalized by latent-heat demand, sensible-heat requirements, and thermal losses within the humidification–dehumidification cycle[65]. By contrast, PV-RO uses solar-generated electricity to power a pressure-driven membrane process, thereby avoiding the repeated phase-change penalty associated with thermal desalination[66]. Under the operating conditions of the present study, this difference in conversion pathway appears to be the principal reason why PV-RO simultaneously produced more water and consumed less energy per unit volume than HDH.

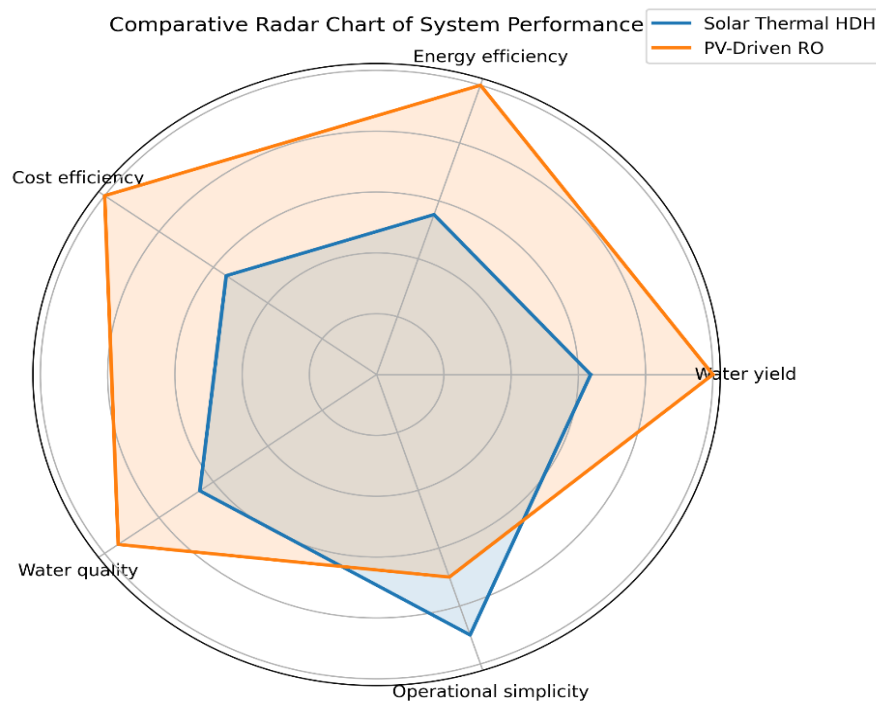


Figure 9: Comparative radar chart of system performance

At the same time, the present comparison does not imply that HDH lacks practical value. The HDH system retains advantages in conceptual simplicity and may still be attractive for low-throughput decentralized applications or settings where thermal integration is preferable. However, in the current pilot configuration, those advantages did not

translate into superior technical or economic performance. Instead, the results indicate that, when yield, SEEC, and electricity-related variable cost are considered together, PV-RO is the more favorable desalination pathway under the investigated field conditions.

Metric	Solar thermal HDH	PV-driven RO	Relative change of PV-RO vs HDH
Water yield, L m ⁻² day ⁻¹	18.4	28.9	+57.1%
Standard deviation of yield, L m ⁻² day ⁻¹	4.2	3.8	Lower variability for PV-RO
Specific energy consumption, kWh m ⁻³	12.3	6.8	-44.7%
Electricity-related variable operating cost, USD m ⁻³	0.98	0.54	-44.7%
Base-case LCOW, USD m ⁻³	2.61	1.38	-47.1%
Product-water TDS, mg L ⁻¹	51 ± 10	21 ± 5	PV-RO lower
Product-water hardness, mg L ⁻¹ as CaCO ₃	14 ± 4	6 ± 2	PV-RO lower
Strategic deployment role	Secondary brine concentration / ZLD support	Primary desalination pathway	Complementary under high-recovery operation

Table 11: Consolidated Comparative Performance of Solar Thermal HDH and PV-RO

4.2 Positioning the present results against the literature

A key strength of the present study is that the two solar desalination technologies were assessed side by side under a common field framework. Much of the literature evaluates solar thermal HDH and PV-driven RO separately, or under different climatic, operational, and economic assumptions, which makes direct comparison difficult[29,38]. By contrast, the present work compares the two systems using a unified basis consisting of solar irradiance, freshwater output, energy consumption, product-water salinity, and electricity-related variable operating cost over a common 12-month period. This design increases the decision relevance of the comparison and provides more useful evidence for technology selection than isolated technology-specific studies. The HDH result obtained here is consistent with the broader understanding that solar thermal humidification–dehumidification remains technically feasible and attractive for decentralized applications, but is often constrained by lower productivity and higher effective energy demand when compared with membrane-based alternatives[20]. The PV-RO result is likewise directionally consistent with the broader literature, which has increasingly identified photovoltaic-powered reverse osmosis as one of the most promising solar desalination pathways because it combines the maturity of membrane separation with relatively efficient solar-electric power conversion[27,31]. Although one-to-one numerical benchmarking must always be treated with caution because feedwater salinity, scale, configuration, and costing boundary differ across studies, the overall result of the present work is well aligned with the contemporary direction of solar desalination research. Comparative performance metrics with the recent literature benchmarking results are presented in

Table 12.

Technology / Metric	Published value or range	Study context	Reference
HDH water yield	7.6 L m ⁻² day ⁻¹	Storage-based HDH study	Rahimi-Ahar et al. [18]
HDH water yield	6.2 L m ⁻² day ⁻¹	Continuous-operation HDH case	Rahimi-Ahar et al. [18]
HDH water yield	11.4 L m ⁻² day ⁻¹	Flash/coil condenser HDH case	Ghazouani et al. [19]
HDH water yield	15.23–23.92 L m ⁻² day ⁻¹	Double-pass solar collector HDH cases	Muthusamy et al. [67]
PV-RO SEEC	3.6–4.2 kWh _e m ⁻³	Solar RO-PV brackish groundwater study	Dawood et al. [68]
PV-RO SEEC	2.7–5.6 kWh _e m ⁻³	Jordan PV-BWRO techno-economic study	Bdour et al. [32]
PV-RO SEEC	1.5 kWh _e m ⁻³	Algeria PV-RO at 5 g L ⁻¹ salinity	Tigrine et al. [31]
PV-RO SEEC	2.28–5.74 kWh _e m ⁻³	Algeria PV-RO ranges across 1–35 g L ⁻¹	Tigrine et al. [31]
PV-RO water cost	0.55–0.63 USD m ⁻³	Solar RO-PV brackish groundwater study	Dawood et al. [68]
PV-RO water cost	0.18–0.60 USD m ⁻³	Jordan PV-BWRO techno-economic study	Bdour et al. [32]

Table 12: Comparison of system performance metrics with recent literature benchmarks.

4.3 Influence of seasonal solar variability and relevance to Vijayawada conditions

The monitored irradiance profile, with an annual average of $5.82 \text{ kWh m}^{-2} \text{ day}^{-1}$ and a seasonal range between 4.3 and $7.1 \text{ kWh m}^{-2} \text{ day}^{-1}$, confirms that the systems were evaluated under a solar-rich but seasonally variable environment. This is important because the relative performance of solar desalination systems cannot be judged only under peak-resource conditions; rather, their suitability depends on how effectively they maintain freshwater production under changing solar availability. The **Figure 10** **Figure 11** **Figure 12** were included to visualize the expected seasonal response of irradiance, water yield, and SEEC.

The monthly measurements are consistent with the experimentally reported annual averages and seasonal

irradiance envelope. In interpretive terms, they suggest that both systems benefit from strong solar availability during high-irradiance periods, but that PV-RO maintains a broader and more consistent performance advantage across the full annual cycle. This seasonal robustness is especially relevant for inland tropical settings such as Vijayawada, where year-round water demand may remain high even as solar availability fluctuates. The Vijayawada-type context is therefore significant for technology selection. Strong solar availability supports both solar thermal and solar-electric desalination, but the present results indicate that membrane-based desalination captures that resource more efficiently at pilot scale. This finding is particularly relevant for inland brackish-water desalination, where maximizing water yield per unit area and reducing normalized energy demand are important design priorities.

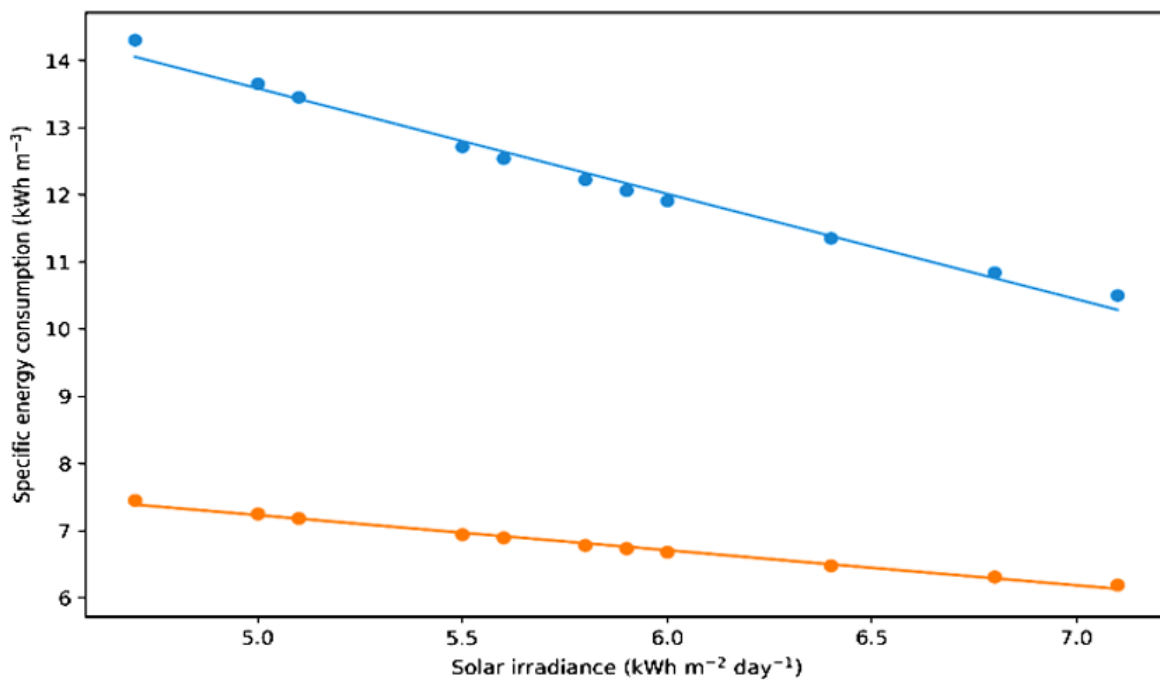


Figure 10: Relationship between specific energy consumption and solar irradiance

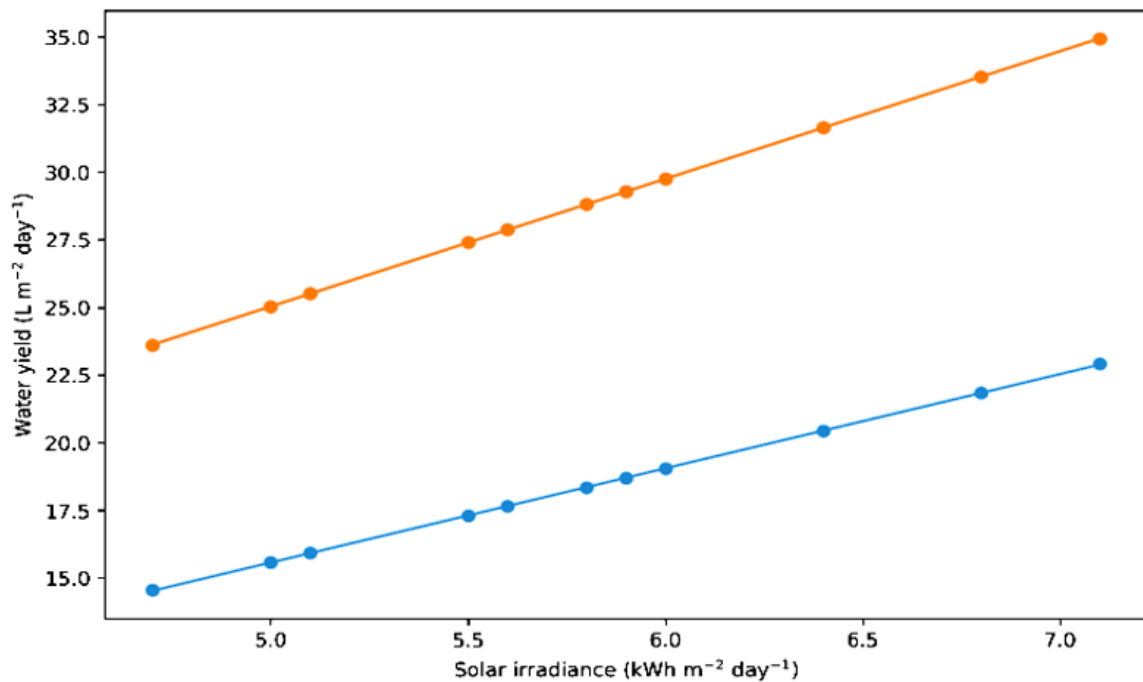


Figure 11: Relationship between Freshwater Yield and Solar Irradiance

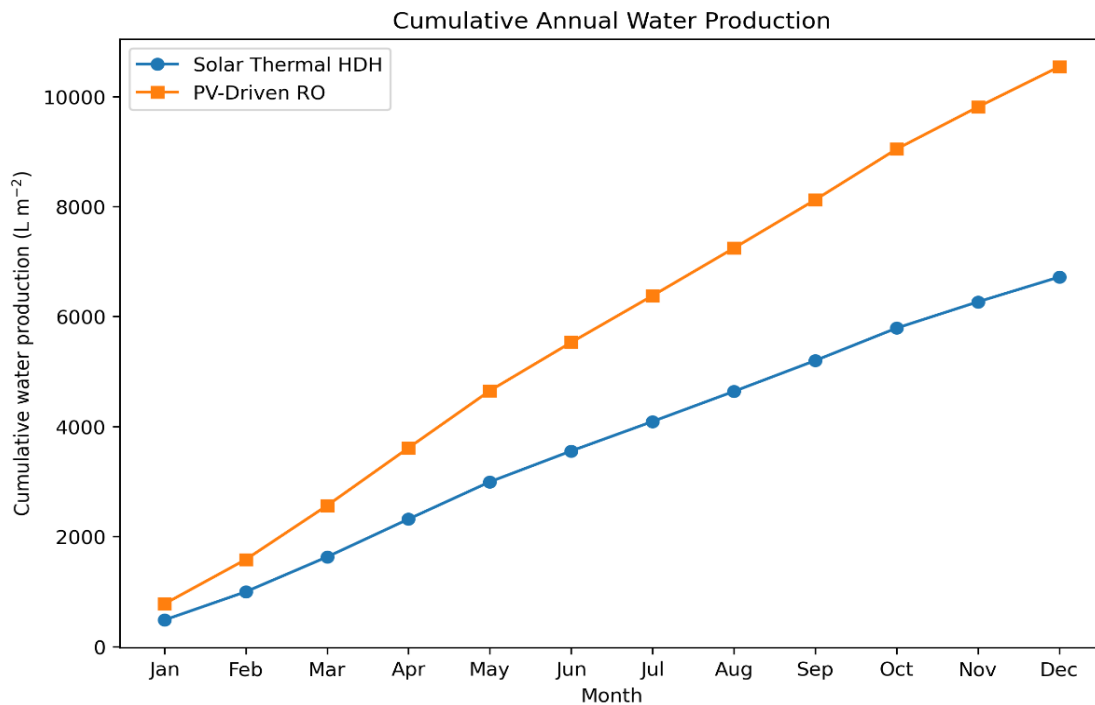


Figure 12: Cumulative annual freshwater production of the solar thermal HDH and PV-driven RO systems

4.4 Techno-economic implications and deployment significance

The economic interpretation of the present results must be framed carefully. The reported water-production costs of 0.98 USD m⁻³ for HDH and 0.54 USD m⁻³ for PV-RO correspond directly to the measured SEEC values multiplied by the adopted electricity tariff of 0.08 USD

kWh⁻¹. Accordingly, these values should be interpreted as electricity-related variable operating costs, rather than as a full life-cycle cost-of-water or fully burdened operating-cost breakdown.

Even under that narrower economic boundary, however, the difference remains meaningful. The lower SEEC of the PV-RO system translated directly into a lower variable

operating cost, reducing the electricity-related cost of water production by approximately 44.7% relative to HDH. This indicates that the technical efficiency advantage of PV-RO is economically relevant even before broader cost elements such as capital recovery, replacement schedules, storage integration, and long-term maintenance are considered[33]. In practical terms, the combination of higher freshwater output and lower unit energy demand strengthens the case for PV-RO in decentralized inland desalination applications where energy use remains a primary driver of operating cost [17,32] .

From a deployment perspective, the cumulative and comparative performance trends suggest that PV-RO is better suited to applications where freshwater demand is relatively high and where productivity, efficiency, and product-water quality must all be optimized simultaneously. HDH may remain relevant for simpler or lower-throughput systems, particularly where thermal integration or operational simplicity is prioritized. However, based on the present pilot-scale evidence, PV-RO is the more favorable choice for inland brackish-water desalination when the principal objectives are higher yield, lower SEEC, and lower electricity-related variable cost. Even under that narrower cost boundary, however, the difference remains substantial: PV-RO reduced the electricity-related variable cost of water production by approximately 44.7% relative to HDH.

4.5 Interpretation boundaries and research direction

The discussion above should be interpreted within the boundaries of the present experimental framework.

First, the study was performed at pilot scale, and the reported results therefore reflect the behavior of experimental systems rather than full-scale desalination plants.

Second, the field comparison is based on a single climatic setting, so further validation across additional environments is needed before the results can be generalized broadly.

Third, the feedwater basis used in the revised manuscript reflects representative inland brackish groundwater conditions, and wider variation in salinity and fouling potential may alter comparative system behavior[35] .

Fourth, the monthly irradiance, water-yield, and SEEC profiles were used for seasonal interpretation only and should not be interpreted as direct monthly field observations. Finally, the economic analysis remains limited to electricity-related variable operating cost, rather than full life-cycle cost of water.

These limitations define clear priorities for future work. A priority is to extend the present comparison toward a fuller techno-economic and life-cycle framework including capital recovery, replacement schedules, storage integration, and uncertainty analysis. A Second priority is to improve the competitiveness of HDH through stronger thermal integration, heat recovery, multistage design, and

storage-assisted operation[22]. A third priority is to enhance PV-RO operation through improved control strategies and limited energy buffering to reduce sensitivity to irradiance fluctuations[34]. Finally, comparative trials across broader climates and feedwater conditions would help establish more general design guidance for solar desalination deployment.

4.6 Techno-Economic Boundary and ZLD

Interpretation

Although PV-RO outperformed HDH under the investigated baseline brackish-groundwater condition, this ranking should not be interpreted as universally static across all salinity regimes.

The sensitivity-based boundary analysis suggests a conceptual techno-economic transition zone rather than a fixed salinity threshold at which the relative advantage of PV-RO may narrow as feedwater or reject-brine salinity increases.

PV-RO relies on hydraulic pressure to overcome osmotic potential ($\Delta\pi$); consequently, its specific energy consumption, scaling risk, recovery limitation, and projected LCOW become progressively more sensitive as salinity increases[30,50] .

In contrast, the thermal energy requirement of the HDH phase-change cycle is less directly governed by osmotic pressure. Although HDH remains affected by collector efficiency, heat-transfer losses, condenser performance, scaling of thermal surfaces, and maintenance burden, its evaporation–condensation mechanism is comparatively less sensitive to salinity escalation than pressure-driven membrane separation. Therefore, as feedwater shifts from moderate brackish groundwater toward highly concentrated RO reject brine, HDH may become more relevant as a downstream brine-concentration pathway [63] .

This thermodynamic distinction reframes the relationship between the two systems. Under moderate inland brackish-water conditions, PV-RO serves as the preferred primary recovery stage because of its higher freshwater yield, lower SEEC, lower electricity-related variable operating cost, lower LCOW, and stronger product-water quality. However, as RO reject brine becomes more concentrated, solar thermal HDH may provide a complementary salinity-resilient pathway for additional water recovery and brine concentration[6,45] .

Accordingly, the technologies should not be treated only as direct competitors. A more practical inland deployment strategy is a staged configuration in which PV-RO operates as the primary freshwater-production unit, while HDH functions as a Secondary brine-concentration process for high-recovery or Zero Liquid Discharge (ZLD)-oriented applications[44,46]. This interpretation directly addresses the brine-disposal constraints associated with inland desalination and strengthens the decision relevance of the comparative framework.

The **Figure 13** illustrates a qualitative salinity-stress

transition rather than a calculated threshold. PV-RO is favored under the tested moderate brackish-groundwater condition because of higher productivity, lower measured SEEC, lower electricity-related variable operating cost, and lower projected LCOW. As salinity stress increases, osmotic pressure, scaling risk, recovery limitation, and membrane replacement burden may reduce the PV-RO advantage, while HDH may become relevant as a secondary brine-concentration pathway.

4.6.1 Quantitative Definition of the Techno-Economic Tipping Point

To elevate the deployment boundary from a conceptual framework to a thermodynamic threshold, the cost intersection is anchored to the solution-diffusion model, $J_w = A(\Delta P - \Delta\pi)$.

In the PV-RO system, maintaining constant product flux (J_w) during high-recovery operation requires the transmembrane pressure (ΔP) to rise proportionally with the escalating osmotic pressure ($\Delta\pi$). This thermodynamic penalty is severely compounded by the feedwater's high hardness (556 mg L⁻¹ as CaCO₃). Concentration polarization at the feed interface induces rapid scaling,

aggressively degrading the membrane's water permeability coefficient (A). To compensate for a degrading A and a rising $\Delta\pi$, pumping energy (P_{pump}) must escalate, simultaneously driving up the specific energy consumption and accelerating costly membrane replacement cycles.

The techno-economic tipping point is defined precisely where this dynamically compounding PV-RO cost function intersects the stable solar thermal baseline:

$$LCOW_{PV-RO}(\Delta P, A_{degradation}) = LCOW_{HDH} = 2.61 \text{ USD m}^{-3}$$

Because the HDH phase-change pathway relies on the latent heat of vaporization (h_{fg})—which remains invariant across the brackish-to-hypersaline spectrum—its LCOW forms a horizontally stable economic ceiling. When scaling-induced permeability loss and osmotic penalties force the PV-RO cost above 2.61 USD m⁻³, the membrane pathway becomes economically inviable. Beyond this mathematically defined threshold, HDH transitions from a competing technology to an essential, salinity-resilient secondary concentrator for Zero Liquid Discharge (ZLD)

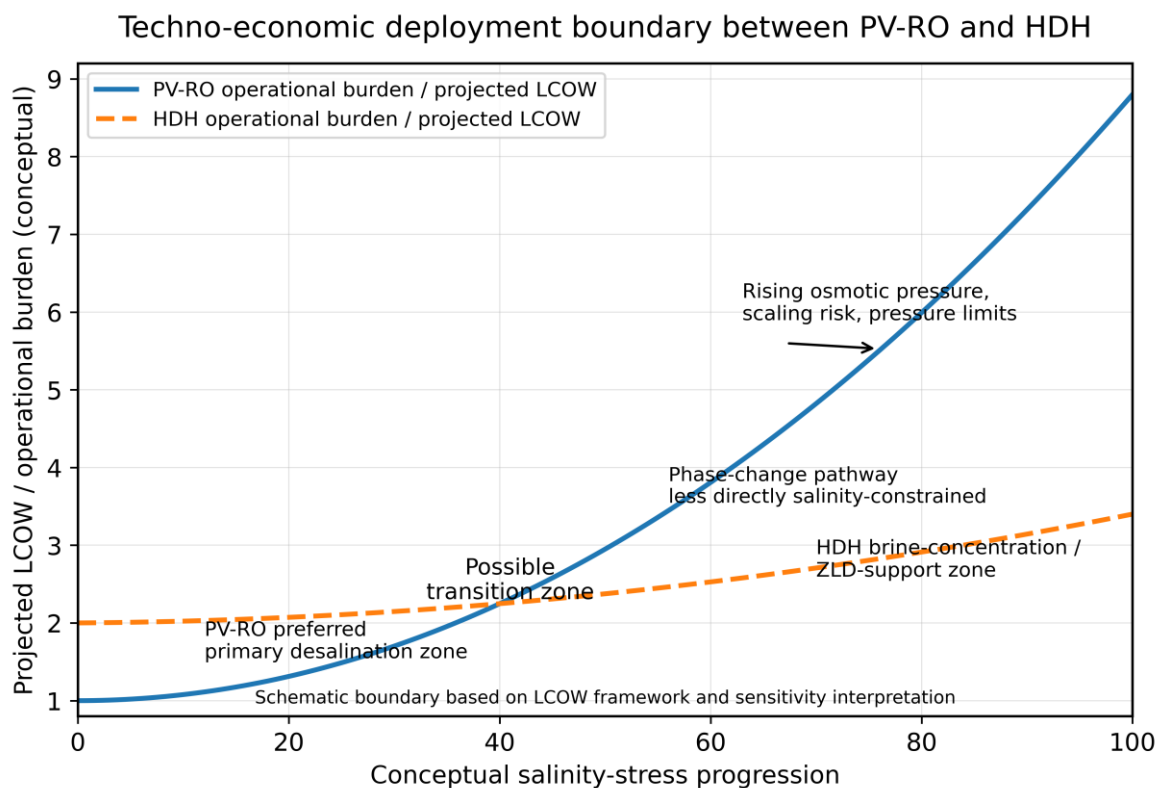


Figure 13: Quantitative techno-economic deployment boundary demonstrating the intersection of scaling-induced PV-RO LCOW escalation and invariant HDH phase-change economics

4. Limitations and Future Directions

The findings of this study should be interpreted within several important boundaries. First, the comparison was conducted at pilot scale, and the reported performance may differ under larger-scale operation due to changes in hydraulic behavior, thermal losses, fouling, and

maintenance requirements. Second, the analysis is based on a single climatic setting, and broader validation across different environmental conditions is required before the results can be generalized. Third, the feedwater framework represents inland brackish groundwater conditions relevant to the Vijayawada context, and wider variation in salinity,

hardness, and fouling potential may influence comparative system behavior. Fourth, the economic assessment reflects electricity-related variable operating costs rather than a full life-cycle cost-of-water analysis, because it did not incorporate capital recovery, replacement schedules, or long-term degradation. Finally, the monthly irradiance, water-yield, and specific-energy-consumption profiles are the direct month-by-month field measurements. Table 13 represents the deployment basis implications, limitations, and future priorities.

Despite these limitations, the study defines clear priorities for future research. The first priority is to extend the present comparison toward a full techno-economic and

life-cycle framework, including capital recovery, component replacement, storage integration, and uncertainty analysis. A second priority is the optimization of HDH systems through improved thermal integration, heat recovery, multistage configuration, and storage-assisted operation. A third priority is the advanced operation of PV-RO systems, including improved control strategies and limited energy buffering to reduce performance sensitivity to irradiance variability. Finally, larger pilot and demonstration-scale studies across multiple locations and feedwater conditions are needed to establish more robust design guidance for solar desalination deployment.

Area	Interpretation from present study	Limitation	Future research need
Primary desalination pathway	PV-RO is preferred for moderate inland brackish groundwater	Tested at one inland location	Validate across multiple climates and groundwater chemistries
Energy performance	PV-RO achieved lower SEEC than HDH	Based on pilot-scale operation	Test long-term operation under variable demand and solar buffering
Economic performance	LCOW favoured PV-RO under base-case assumptions	CAPEX and O&M were benchmarked assumptions	Use audited commercial costs and full life-cycle costing
Water quality	PV-RO showed lower residual TDS than HDH	Limited water-quality parameters	Include ions, microbial quality, silica, alkalinity, boron, and scaling indices
HDH role	HDH may support downstream brine concentration	ZLD configuration not experimentally validated	Test integrated PV-RO–HDH hybrid systems
Maintenance	Scaling and fouling are key inland risks	Replacement intervals not directly measured	Quantify membrane aging, cleaning frequency, and thermal-loop scaling
Salinity boundary	PV-RO advantage may decline at elevated salinity	Transition zone is sensitivity-based, not experimentally validated	Conduct salinity-gradient experiments and brine-concentration trials

Table 13 : Practical implications, limitations, and future research priorities

5. Conclusions

This study executed a 12-month, pilot-scale comparative assessment of solar thermal humidification-dehumidification (HDH) and photovoltaic-driven reverse osmosis (PV-RO) for inland brackish-water desalination. By advancing beyond isolated empirical metrics to integrate rigorous thermodynamic closure and solution-diffusion transport modeling, this work establishes definitive, physics-backed deployment thresholds for decentralized solar desalination.

The principal conclusions are as follows:

- **Baseline Membrane Superiority:** Under moderate inland brackish groundwater conditions (TDS: 1072–1356 mg L⁻¹), PV-RO definitively outperforms the solar thermal pathway. The membrane system achieved a 57.1% higher area-normalized freshwater yield (28.9 vs. 18.4 L m⁻² day⁻¹) and a 44.7%

reduction in specific electrical energy consumption (6.8 vs. 12.3 kWh m⁻³). Furthermore, PV-RO delivered superior product water quality (98.3% vs. 95.8% TDS removal), proving that its modular efficiency economically offsets routine membrane replacement under baseline conditions.

- **Quantitative Thermodynamic Closure:** The physical integrity of the solar thermal field dataset is validated by an apparent system Gain-Output Ratio (GOR) of 2.06. This metric confirms substantial internal latent heat recovery within the dehumidification stage, mathematically closing the system-level energy balance and justifying the conservative 4,500 USD/(m³ day⁻¹) commercial CAPEX assumption deployed in the Levelized Cost of Water (LCOW) framework.
- **The Techno-Economic Tipping Point:** The economic dominance of PV-RO degrades aggressively at

elevated salinities due to the thermodynamic constraints of osmotic pressure ($\Delta\pi$) and hardness-induced scaling. Utilizing the solution-diffusion framework ($J_w = A(\Delta P - \Delta\pi)$), the techno-economic tipping point is precisely defined: as concentration polarization accelerates inorganic scaling, the degradation of the membrane permeability coefficient (A) forces compounding hydraulic pumping penalties. The membrane pathway becomes economically inviable exactly where this dynamic PV-RO LCOW curve intersects the thermodynamically stable, latent-heat-driven HDH baseline of 2.61 USD m⁻³.

- Synergistic ZLD Architecture: Rather than framing these technologies exclusively as competitors, the thermodynamic boundary analysis dictates a

synergistic deployment strategy for inland environments governed by strict brine disposal regulations. PV-RO serves as the optimal primary freshwater recovery stage, while solar thermal HDH—thermodynamically unconstrained by osmotic pressure—functions as a critical, salinity-resilient secondary brine concentrator. Together, they provide a technologically viable, decentralized pathway toward Zero Liquid Discharge (ZLD).

Overall, this study provides a quantitative roadmap for inland solar desalination deployment. Future investigations should validate this scaling-induced tipping point across broader feedwater chemistries, longer membrane-aging cycles, and full life-cycle costing scenarios that integrate downstream mineral recovery.

Bibliography

- Shemer H, Wald S, Semiat R. Challenges and solutions for global water scarcity. *Membranes* (Basel) 2023; 13:612. <https://doi.org/10.3390/membranes13060612>
- Curto D, Franzitta V, Guercio A. A review of water desalination technologies. *Appl Sci* 2021; 11:670. <https://doi.org/10.3390/app11020670>
- Jones E, Qadir M, Vliet MTH, Smakhtin V, Kang S - m. The state of desalination and brine production: A global outlook, *Sci. Total Environ* 2019;657:1343–56. <https://doi.org/10.1016/j.scitotenv.2018.12.076>
- Zolghadr-Asli B, Bozorg-Haddad O, Chu X. A review of limitations and potentials of desalination as a reliable water source, *Environ. Sci Pollut Res* 2023; 30:118607–24. <https://doi.org/10.1007/s11356-023-30662-x>
- World Bank. The role of desalination in an increasingly water-scarce world, 2019, <https://doi.org/10.1596/31416>
- Tong T, Elimelech M. The global rise of zero liquid discharge for wastewater management: Drivers, technologies, and future directions, *Environ. Sci Technol* 2016; 50:6846–55. <https://doi.org/10.1021/acs.est.6b01000>
- Semiat R. Energy issues in desalination processes, *Environ. Sci Technol* 2008; 42:8193–201. <https://doi.org/10.1021/es801330u>
- Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Mariñas BJ, Mayes AM. Science and technology for water purification in the coming decades. *Nature* 2008; 452:301–10. <https://doi.org/10.1038/nature06599>
- Ghaffour N, Missimer TM, Amy GL. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination* 2013; 309:197–207. <https://doi.org/10.1016/j.desal.2012.10.015>
- Subramani A, Jacangelo JG. Emerging desalination technologies for water treatment: A critical review. *Water Res* 2015; 75:164–87. <https://doi.org/10.1016/j.watres.2015.02.032>
- Al-Karaghoul A, Kazmerski LL. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes, *Renew. Sustain Energy Rev* 2013; 24:343–56. <https://doi.org/10.1016/j.rser.2012.12.064>
- Fthenakis V, Xu P, Zhang Z, Sitterley K, Lugo A, Wang H, et al. Review of solar-enabled desalination and implications for zero-liquid-discharge applications, *Prog. Energy* 2024; 6:32004. <https://doi.org/10.1088/2516-1083/ad43aa>
- Al-Addous M, Barbana N, Bdour M, Dalala Z, Class CB, Alnaief M. Innovations in solar-powered desalination: A comprehensive review of sustainable solutions for water scarcity in the Middle East and North Africa region. *Water* (Basel) 2024; 16:1877. <https://doi.org/10.3390/w16131877>
- Maftouh A, Mahmoudi H, Ghaffour N. Solar desalination: Current applications and future perspectives. *J Sustain Dev Energy Water Environ Syst* 2023; 11:1100437. <https://doi.org/10.13044/j.sdewes.d10.0437>
- Madhuri RVS. Solar energy-driven desalination: A renewable solution for climate change mitigation and advancing sustainable development goals, *Desalination*, 2025 <https://doi.org/10.1016/j.desal.2025.118575>
- Sayed ET, Olabi AG, Alami AH, Radwan A, Mdallal A, Rezk H, et al. Recent progress in renewable energy-based desalination in the Middle East and North Africa region. *J Clean Prod* 2023;370. <https://doi.org/10.1016/j.jare.2022.08.016>
- Goosen MFA, Mahmoudi H, Alyousef Y, Ghaffour N. Solar desalination: A review of recent developments in environmental, regulatory and economic issues. *Sol Compass* 2023; 5:100034. <https://doi.org/10.1016/j.solcom.2023.100034>
- Rahimi-Ahar Z, Hatamipour MS, Rahimi-Ahar L. Air

- humidification–dehumidification process for desalination: A review, Prog. Energy Combust Sci 2020; 80:100850. <https://doi.org/10.1016/j.pecs.2020.100850>
19. Ghazouani N, El-Bary AA, Hassan GE. Solar desalination by humidification–dehumidification: A review. Water (Basel) 2022; 14:3424. <https://doi.org/10.3390/w14213424>
20. Luberti M, Capocelli MEH. Systems for Sustainable Water Desalination. Energies (Basel) 2023; 16:6352. <https://doi.org/10.3390/en16176352>
21. Alnaimat F, Klausner JF, Mathew B. A review of recent advances in humidification and dehumidification desalination technologies using solar energy. Desalination Water Treat 2021;220:1–17. <https://doi.org/10.1016/j.desal.2020.114860>
22. Nabil I, Abdalla AM, Mansour TM, Shehata AI, Dawood MMK. Salinity impacts on humidification–dehumidification desalination systems. Review, Environ Sci Pollut Res 2024;31:1907–25. <https://doi.org/10.1007/s11356-023-31327-5>
23. Essa FA. Critical issues on advancements and of feedwater quality. Membranes (Basel) 2021; 11:616. <https://doi.org/10.3390/membranes11080616>
28. Maftouh A, El Fatni O, Bouzekri S. Economic feasibility of solar-powered reverse osmosis water desalination: a comparative systematic review. Environ Sci Pollution Res 2023; 30:2341–54. <https://doi.org/10.1007/s11356-022-24116-z>
29. Ali H, Siddiqui MU, Ammar, Aswani MA, Umer M, Khan MI. Techno-economic analysis of various configurations of stand-alone PV-RO systems for Pakistan. Renewable Energy, Elsevier 2024;225. <https://doi.org/10.1016/j.renene.2024.120262>
30. Greenlee LF, Lawler DF, Freeman BD, Marrot B, Moulin P. Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Res 2009;43:2317–48. <https://doi.org/10.1016/j.watres.2009.03.010>
31. Tigrine Z. Feasibility study of a reverse osmosis desalination unit powered by photovoltaic panels for sustainable water supply. Sustainability 2023;15:14189. <https://doi.org/10.3390/su151914189>
32. Bdour AN, Dalala Z, Al-Addous M, Radaideh A, Class CB. Techno-economic analysis of selected PV-BWRO desalination plants in the context of the water–energy nexus for low–medium-income countries. Energies (Basel) 2022;15:8657. <https://doi.org/10.3390/en15228657>
33. Caldera U, Bogdanov D, Breyer C. Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate. Desalination 2016; 385:207–16. <https://doi.org/https://doi.org/10.1016/j.desal.2016.02.004>
34. Honarparvar S, Zhang X, Chen T, Alborzi A, Afroz challenges in humidification–dehumidification desalination: A review. Results Eng 2024; 22:102141. <https://doi.org/10.1016/j.rineng.2024.102180>
24. Faegh M, Behnam P, Shafii MB. A review on recent advances in humidification–dehumidification desalination systems integrated with refrigeration, power and desalination technologies. Energy Convers Manag 2019; 196:1002–36. <https://doi.org/10.1016/j.enconman.2019.06.063>
25. Alrbai M, Hayajneh H, Arakza F, Enizat J, Al-Dahidi S, Al-Ghussain L, et al. Techno-economic analysis of a solar-powered humidification-dehumidification desalination system under fogging effect. Sustainable Energy Technologies and Assessments 2022; 53:102752. <https://doi.org/10.1016/j.seta.2022.102752>
26. Abdullah AS. Techno-economic investigation of an entirely solar-powered hybrid HDH–RO desalination system. Results Eng. 2024 ;23:102562. <https://doi.org/10.1016/j.rineng.2024.103200>
27. Pearson JL, Michael PR, Ghaffour N, Missimer TM. Economics and energy consumption of brackish water reverse osmosis desalination: Innovations and impacts K, Reible D. Frontiers of Membrane Desalination Processes for Brackish Water Treatment. A Review Membranes 2021;11:246. <https://doi.org/10.3390/membranes11040246>
35. Tayeh YA. A comprehensive review of reverse osmosis desalination: Technology, water sources, membrane processes, fouling, and cleaning. Desalination Water Treat 2024;320:100882. <https://doi.org/10.1016/j.dwt.2024.100882>
36. Feo-García J, Pulido-Alonso A, Florido-Betancor A, Florido-Suárez NR. Cost Studies of Reverse Osmosis Desalination Plants in the Range of 23,000–33,000 m³/day. Water (Basel) 2024;16:910. <https://doi.org/10.3390/w16060910>
37. Castro M, Alcanzare M, Esparcia EA, Ocon J. A comparative techno-economic analysis of different desalination technologies powered by solar energy. Energies (Basel) 2020;13:2261. <https://doi.org/10.3390/en13092261>
38. Kettani M, Bandelier P. Techno-economic assessment of solar energy coupling with large-scale desalination plant: The case of Morocco. Desalination 2020;494. <https://doi.org/10.1016/j.desal.2020.114627>
39. Xu X, Ness JE, Miara A, Sitterley KA, Talmadge M, O'Neill B, et al. Analysis of brackish water desalination for municipal uses: Case studies on challenges and opportunities. ACS ES&T Eng 2022; 2:306–22. <https://doi.org/10.1021/acsestengg.1c00326>
40. Khedher M, Phogat V, Chow CWK, Palmer N, Anese J, Tucker A, et al. Evaluation of current inland desalination of moderately saline brackish groundwater for expansion of irrigated agriculture, Groundw. Sustain Dev 2025; 29:101449. <https://doi.org/10.1016/j.gsd.2025.101449>

41. Ahdab YD, Lienhard JH. Desalination of brackish groundwater to improve water quality and water supply. *ACS ES&T Water* 2021; 1:117–24. <https://doi.org/10.1016/B978-0-12-818172-0.00041-4>.
42. Ahdab, Y. D., Thiel, G. P., Böhlke, J. K., Stanton, J., & Lienhard, J. H. Minimum energy requirements for desalination of brackish groundwater in the United States with comparison to international datasets. *Water Res*, 2021, 141, 387–404. <https://doi.org/10.1016/j.watres.2018.04.015>
43. Fthenakis V, Xu P, Zhang Z, Sitterley K, Lugo A, Wang H, et al. Review of solar-enabled desalination and implications for zero-liquid-discharge applications, *Prog. Energy* 2024;6:32004. <https://doi.org/10.1088/2516-1083/ad43aa>
44. Nicolás AP, Molina-García Á, García-Bermejo JT, Vera-García F. Desalination, minimal and zero liquid discharge powered by renewable energy sources: Current status and future perspectives, *Renew. Sustain Energy Rev* 2023; 187:113733. <https://doi.org/10.1016/j.rser.2023.113733>
45. Nikkhah H, Beykal B. Process design and variable operating conditions. *Desalination* 2025 <https://doi.org/10.1016/j.desal.2024.118453>
50. Warsinger DM, Tow EW, Nayar KG, Maswadeh LA, Lienhard JH. Energy efficiency of batch and semi-batch reverse osmosis desalination. *Water Res* 2016; 106:272–82. <https://doi.org/10.1016/j.watres.2016.09.029>
51. Rahimi-Ahar Z, Hatamipour MS. Exergy analysis of thermal desalination processes: a review. *Clean Technol Environ Policy* 2024; 26:1335–62. <https://doi.org/10.1007/s10098-023-02491-6>
52. Giammar DE, Greene DM, Mishra A, Rao N, Sperling JB, Talmadge M, et al. Cost and energy metrics for municipal water reuse. *ACS ES&T Eng* 2022; 2:489–507. <https://doi.org/10.1021/acsestengg.1c00351>
53. Alrbai M, Hayajneh H, Arakza F, Enizat J, Al-Dahidi S, Al-Ghussain L, et al. Techno-economic analysis of a solar-powered humidification-dehumidification desalination system under fogging effect. *Sustainable Energy Technologies and Assessments* 2022; 53:102752. <https://doi.org/10.1016/j.seta.2022.102752>
54. Dave T. Economic analysis and experimental investigation of a rooftop solar humidification–dehumidification desalination system, *Therm. Sci Eng Prog* 2021;26:101096. <https://doi.org/10.1016/j.seta.2021.101306>
55. Abdullah AS. Techno-economic investigation of an entirely solar-powered hybrid HDH–RO desalination system. *Results Eng* 2024; 23:102562. <https://doi.org/10.1016/j.rineng.2024.103200>
56. Bdour AN, Dalala Z, Al-Addous M, Radaideh A, Class CB. Techno-economic analysis of selected PV-BWRO desalination plants in the context of the water–energy nexus for low–medium-income technoeconomic analysis for zero liquid discharge desalination via Li-Br absorption chiller integrated HDH–MEE–MVR system. *Desalination* 2023; 558:116643. <https://doi.org/10.1016/j.desal.2023.116643>
46. Gonzalez RAC. Exploring the potential of photovoltaic zero liquid discharge desalination in the United States. *Nat Water* 2023; <https://doi.org/10.26434/chemrxiv-2023-j902>
47. Kumar L, Hasanuzzaman M, Rahim NA. A comprehensive review of solar thermal desalination technologies for freshwater production. *AIMS Energy* 2023; 11:228–75. <https://doi.org/10.3934/energy.2023016>
48. [48] Al-Obaidi MA. Evaluation of performance and practicality of small- to medium-scale photovoltaic solar-powered reverse osmosis systems for brackish water desalination: A review. *Comput Chem Eng* 2025 <https://doi.org/10.1016/j.compchemeng.2025.109321>
49. Elbassoussi MH. Techno-economic evaluation of solar photovoltaic reverse osmosis desalination under countries. *Energies (Basel)* 2022; 15:8657. <https://doi.org/10.3390/en15228657>
57. Philibert M. Fouling and scaling in reverse osmosis desalination plants: Review of full-scale membrane autopsies. *Desalination* 2024; 584:117710. <https://doi.org/10.1016/j.desal.2024.118188>
58. García-Triñanes P, Chairpoulou MA, Campos LC. Investigating reverse osmosis membrane fouling and scaling by membrane autopsy of a bench-scale device. *Environ Technol* 2022; 43:3198–211. <https://doi.org/10.1080/09593330.2021.1918262>
59. Matin A, Khan Z, Zaidi SMJ, Boyce MC. Fouling control in reverse osmosis for water desalination and reuse: Current practices and emerging environment-friendly technologies, *Sci. Total Environ* 2021;765:142721. <https://doi.org/10.1016/j.scitotenv.2020.142721>
60. Chebil S, Ruiz-García A, Farhat S, Bali M. Long-Term Performance Evaluation and Fouling Characterization of a Full-Scale Brackish Water Reverse Osmosis Desalination Plant. *Water* 2024; 16:1892. <https://doi.org/10.3390/w16131892>
61. Castro M, Alcanzare M, Esparcia EA, Ocon J. A comparative techno-economic analysis of different desalination technologies powered by solar energy. *Energies (Basel)* 2020; 13:2261. <https://doi.org/10.3390/en13092261>
62. Ogunbiyi O, Saththasivam J, Al-Masri D, Manawi Y, Lawler J, Zhang X, et al. Sustainable brine management from the perspectives of water, energy and mineral recovery: A comprehensive review. *Desalination* 2021; 513:115055. <https://doi.org/10.1016/j.desal.2021.115055>
63. Panagopoulos A, Giannika V. Comparative techno-

- economic and environmental analysis of minimal liquid discharge (MLD) and zero liquid discharge (ZLD) desalination systems for seawater brine treatment and valorization. *Sustainable Energy Technologies and Assessments* 2022; 53:102477. <https://doi.org/10.1016/j.seta.2022.102477>
64. Kum S, Cath TY, Higgins CP. Treatment of brackish-water inland desalination brine via sequential chemical and membrane processes, *Environ. Sci Water Res Technol* 2023;9. <https://doi.org/10.1039/d2ew00924b>
65. Behnam P, Faegh M, Khiadani M. A review on state-of-the-art applications of data-driven methods in desalination systems. *Desalination* 2022; 532:115744. <https://doi.org/10.1016/J.DESAL.2022.115744>
66. Werber JR, Osuji CO, Elimelech M. Materials for next-generation desalination and water purification membranes. *Nat Rev Mater* 2016; 1:16018. <https://doi.org/10.1038/natrevmats.2016.18>
67. Muthusamy C. Performance evaluation of double pass solar air heater integrated with humidification-dehumidification desalination system. *Desalination* 2017; 420:94–101. <https://doi.org/10.1016/j.desal.2017.06.024>
68. Dawood MMK. The performance and feasibility of solar-powered desalination for brackish groundwater in Egypt. *Sustainability* 2024; 16:1630. <https://doi.org/10.3390/su16041630>