



UNIVERSITÀ POLITECNICA DELLE MARCHE
Repository ISTITUZIONALE

Solar-Powered Desalination System Combining Reverse Osmosis and Membrane Distillation to Enhance the Recovery Ratio

This is the peer reviewed version of the following article:

Original

Solar-Powered Desalination System Combining Reverse Osmosis and Membrane Distillation to Enhance the Recovery Ratio / Vitulli, P., Sanchez, A.B., Principi, E., Squartini, S., Zaragoza, G.. - (2025), pp. 455-461. (14th International Conference on Renewable Energy Research and Applications, ICRERA 2025 Vienna 27 - 30 October 2025) [10.1109/ICRERA66237.2025.11283655].

Availability:

This version is available at: 11566/361554 since: 2026-08-12T08:06:25Z

Publisher:

Institute of Electrical and Electronics Engineers Inc.

Published

DOI:10.1109/ICRERA66237.2025.11283655

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. The use of copyrighted works requires the consent of the rights' holder (author or publisher). Works made available under a Creative Commons license or a Publisher's custom-made license can be used according to the terms and conditions contained therein. See editor's website for further information and terms and conditions.

This item was downloaded from IRIS Università Politecnica delle Marche (<https://iris.univpm.it>). When citing, please refer to the published version.

Publisher copyright:

IEEE - Postprint/Author's Accepted Manuscript

©2025 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. To access the final edited and published work see 10.1109/ICRERA66237.2025.11283655

(Article begins on next page)

Solar-Powered Desalination System Combining Reverse Osmosis and Membrane Distillation to Enhance the Recovery Ratio

1st Paolo Vitulli
dept. Information Engineering
Università Politecnica delle Marche
Ancona, Italy
p.vitulli@pm.univpm.it

2nd Alejandro Bueso Sánchez
Plataforma Solar de Almería
CIEMAT
Almería, Spain
alejandros.bueso@psa.es

3rd Emanuele Principi
dept. Information Engineering
Università Politecnica delle Marche
Ancona, Italy
e.principi@staff.univpm.it

4th Stefano Squartini
dept. Information Engineering
Università Politecnica delle Marche
Ancona, Italy
s.squartini@staff.univpm.it

5th Guillermo Zaragoza
Plataforma Solar de Almería
CIEMAT
Almería, Spain
guillermo.zaragoza@psa.es

Abstract—This study proposes and evaluates a standalone desalination system powered entirely by solar energy. The system integrates a Reverse Osmosis (RO) unit with Membrane Distillation (MD) units to minimize brine discharge. Both electrical and thermal energy are supplied by Concentrated Photovoltaic/Thermal (CPV/T) collectors. The primary objective of the RO-MD configuration is to enhance freshwater production, measured by the Recovery Ratio (RR), while relying exclusively on renewable energy sources.

The analysis focuses on assessing improvements in RR, the resulting water flow rate, and the system's economic performance, specifically in terms of the Levelized Cost of Water (LCOW) and the amount of electrical energy generated. System performance is evaluated through dynamic simulations conducted over an entire year using real weather data from Almería, Spain.

Results indicate that incorporating MD units in series with RO increases total water output by 7.99 % for a plant designed to operate 10 hours per day in July with an input flow rate of 10 m³/h. This leads to an improvement in water recovery from 41.06 % (RO alone) to 44.34 %. The LCOW is estimated at 6.68 USD/m³, which is lower than that of other desalination technologies powered by renewable energy.

Index Terms—Hybrid Photovoltaic/Thermal collector, Reverse Osmosis, Membrane Distillation, Minimum liquid discharge, Recovery Ratio, Levelized Cost of Water.

I. INTRODUCTION

In 2022, water scarcity affected 34 % of EU land and 41 % of its population, despite a 19 % drop in water abstraction since 2000 [1]. Climate change and increasing consumption are straining freshwater resources. For this reason, desalinating seawater and highly brackish water is attracting growing interest and is increasingly seen as a practical way to address mainly domestic and municipal water demands [2].

Desalination's high energy demands can be mitigated by using renewables like solar power, allowing for low-emission freshwater production [3]. Regions with abundant sunlight and

limited water resources are especially suited for integrating photovoltaic and solar thermal energy with desalination. This aspect has been explored extensively in recent research [3].

Reverse Osmosis (RO) leads EU desalination, making up 88.5 % of capacity due to its scalability, high efficiency, and relatively low water cost (0.45–1.72 USD/m³) compared to other methods [4]. However, RO is characterized by high specific consumption of electrical energy and faces a significant challenge related to brine disposal. Most seawater desalination plants discharge this brine directly into the sea, causing potential environmental harm like eutrophication, increased salinity, and toxicity [5].

Brine, often considered waste, can actually be a valuable resource offering additional freshwater, salts, minerals, metals, chemicals, bioactive compounds, and even energy. To harness these benefits and address the brine disposal problems, approaches like Minimal and Zero Liquid Discharge (MLD/ZLD) have been proposed. To achieve MLD or ZLD, brine is often concentrated through multiple desalination stages for high water recovery. RO brine, for instance, can undergo further treatment via second-stage RO, Membrane Distillation (MD), Forward Osmosis (FO), or Humidification-Dehumidification (HDH) units [6]. MD efficiently recovers water from desalination brine using low-grade heat (60–90 °C), often supplied by solar thermal energy [7] or industrial waste heat.

Photovoltaic/Thermal (PV/T) systems are attractive for desalination as they simultaneously supply heat and electricity [8]. Anand et al. [9] found that PV/T-coupled systems outperform setups using separate photovoltaic and solar thermal units. However, most of these collectors generate low temperature heat (lower than 40 °C) [8]; therefore, they are not optimally suited for certain thermal-based desalination systems

requiring higher-grade heat.

In contrast, Concentrated Photovoltaic/Thermal (CPV/T) systems simultaneously generate high-temperature water and electricity [10], [11], making them a promising technology for various applications, including thermal-based and electrical-based desalination.

Khouya [12] analyzed Reverse Osmosis–Multi-Effect Distillation–Thermal Vapor Compression (RO–MED–TVC) systems powered by CPV/T, comparing their performance across different configurations and assessing economic outcomes in several Middle Eastern countries. The resulting levelized cost of water (LCOW) ranged from 0.424 USD/m³ to 0.466 USD/m³. However, authors did not consider electrical storage, relying on the grid to supplement any energy shortfall from the PV generation system.

Weisenfarth et al. [13] developed a CPV/T–RO–MD system for brackish water desalination, aiming to increase freshwater productivity while simultaneously using the desalination feed water to cool the CPV/T receiver. They also considered the presence of electric storage; however, they did not simulate the system dynamic behavior, limiting the work to the design stage.

However, no studies have investigated a fully renewable-powered desalination system aimed at enhancing the Recovery Ratio (RR), equipped with both thermal and electrical storage, and evaluated under real weather conditions throughout the year.

In this study, we present the design and techno-economic analysis of a low-concentration parabolic trough CPV/T–RO–MD seawater desalination system with integrated thermal and electrical storage, enabling fully stand-alone solar-powered operation. The system combines RO and MD to improve RR, with MD treating the brine from RO to produce additional freshwater. It operates entirely on solar energy, meeting both thermal and electrical demands without greenhouse gas emissions. Using mathematical modeling, we simulate system performance under real weather conditions in Almería over one year, assessing water productivity and long-term economic viability.

The remainder of this paper is structured as follows: Section II provides a description of the studied system, Section III describes the methodology of the investigation, Section IV presents and discusses the results of the analysis, and finally, Section V concludes the paper.

II. SYSTEM DESCRIPTION

The analyzed system is illustrated in Fig. 1. Seawater is initially desalinated using a RO unit, producing both freshwater and brine. The brine is then fed into multiple MD modules connected in parallel. These spiral-wound modules, manufactured by the Dutch company Aquastill and characterized by [14], generate additional freshwater while reducing the volume of discharged brine, thereby increasing the overall RR.

The RO and MD units operate using electrical energy generated by CPV/T collectors. This energy is stored in electrochemical batteries to enable continuous operation, even

TABLE I
MAIN SYSTEM CHARACTERISTICS

Component	Parameter	Value
Reverse Osmosis Membrane Distillation	Inlet flow rate	10 m ³ /h
	Number of units	5
CPV/T	Type	Spiral Wound
	Concentration factor	20
	STC ^a electric power	28.4 kW
	STC cell efficiency, (η_{ref})	29.8 %
	Efficiency coefficient (β_{pv})	-0.00248 °C ⁻¹
	Length of collector, (L)	24 m
	Width of collector, (W)	1.208 m
Heat storage	Number of collector	5
	Water flow rate, ($\dot{m}$)	0.20 kg/s
	Number of tanks	3
	Volume of each tank	18 m ³
Heat exchanger	Number of heat exchangers	2
Electric storage	Number of batteries	4
	Capacity of each battery	11.7 kWh

^a Standard Test Condition

in the absence of sunlight. These batteries also power auxiliary components such as pumps.

MD is driven by thermal energy from the thermal output of the CPV/T collectors. This energy is accumulated in heat storage tanks, which, like the batteries, allow operation during periods of low solar irradiance. The stored thermal energy is delivered to the MD units via a heat exchanger.

The main system characteristics are reported in Table I.

A. Concentrated Photovoltaic/Thermal collector model

The model of CPV/T is based on the principle of energy conservation and is derived from [11], considering a rectangular receiver shown in Fig. 2.

- Energy balance equation of insulation layer:

$$\delta_i \rho_i c_i \frac{dT_i}{dt} = \alpha_i I_g + \frac{\lambda_i}{\delta_i} (T_{abs1} - T_i) - \sigma \varepsilon_i (T_i^4 - T_{sky}^4) - U_{cv,i-amb} (T_i - T_{amb}), \quad (1)$$

where σ is the Stefan-Boltzmann constant. The parameters δ_i , ρ_i , c_i , λ_i , α_i and ε_i represent the thickness, density, specific heat, thermal conductivity, absorptivity and the emissivity of insulator layer respectively; T_i denotes the insulation temperature and I_g is the global solar radiation incident on the sloped surface. T_{sky} is the sky temperature while T_{amb} represents the ambient air temperature.

The convective heat loss coefficient between the insulation and the ambient environment, $U_{cv,i-amb}$, is calculated as follows:

$$U_{cv,i-amb} = 2.8 + 3u, \quad (2)$$

where u is the wind speed.

- Energy balance equation of top layer of absorber substrate:

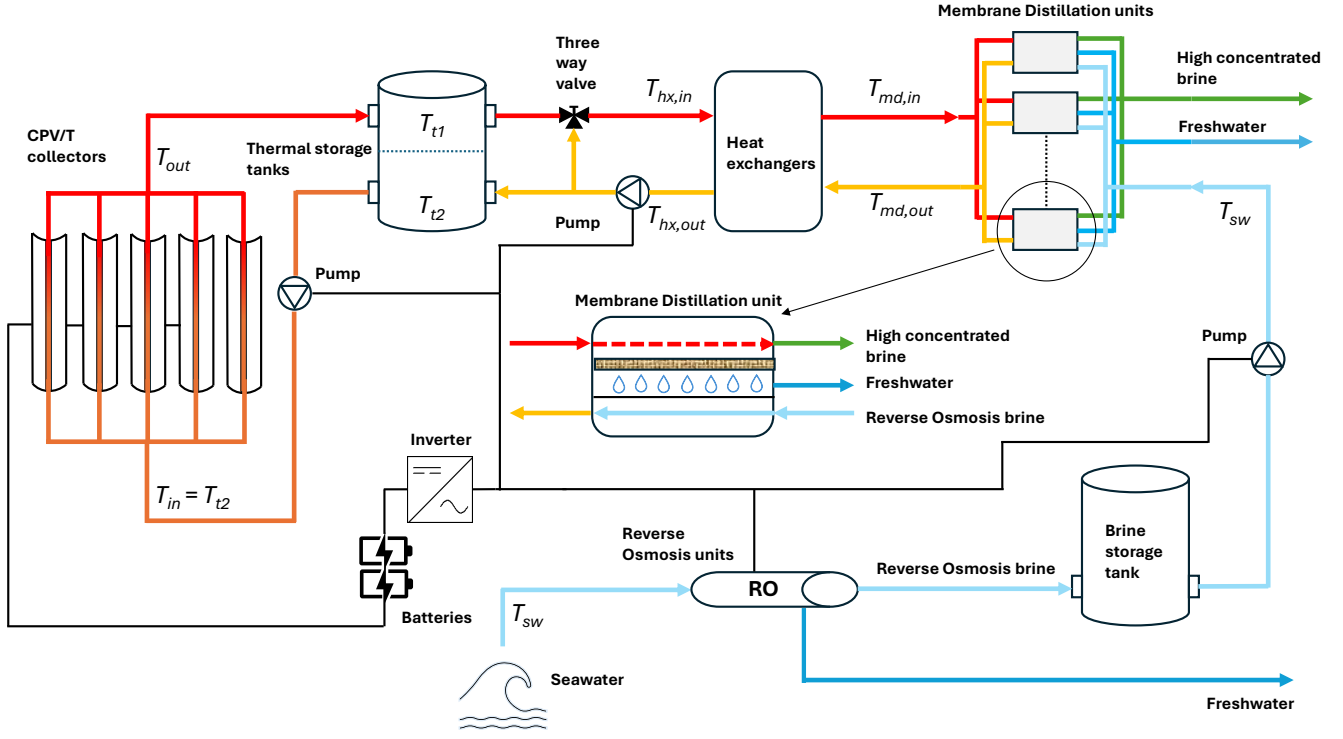


Fig. 1. CPV/T-RO-MD system

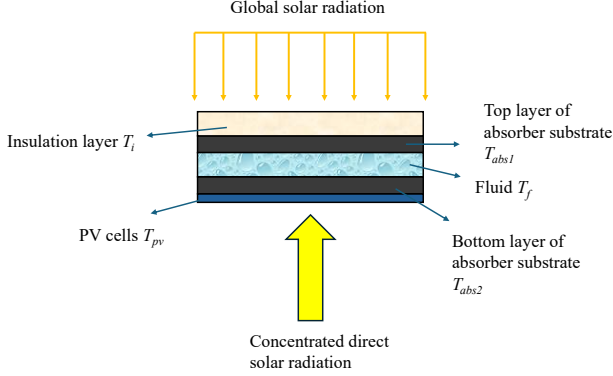


Fig. 2. Rectangular receiver layers

$$\delta_{abs1} \rho_{abs1} c_{abs1} \frac{dT_{abs1}}{dt} = h_f (T_f - T_{abs1}) - \frac{\lambda_i}{\delta_i} (T_{abs1} - T_i), \quad (3)$$

where, δ_{abs1} , ρ_{abs1} , c_{abs1} , T_{abs1} , T_f are the thickness, density, specific heat, temperature of the top layer of absorber and temperature of the fluid respectively. The convective heat transfer coefficient h_f is calculated

as follows,

$$h_f = \frac{Nu_f \lambda_f}{D_h}, \quad (4)$$

in which λ_f is the thermal conductivity of fluid, D_h is the equivalent diameter of the fluid channel and Nu_f is the Nusselt number, estimated as follows:

$$Nu_f = \begin{cases} 0.023 \cdot Re_f^{4/5} \cdot Pr^{0.4} & \text{for } Re_f > 2300 \\ 5.39 & \text{for } Re_f \leq 2300 \end{cases}$$

where Re_f and Pr are the Reynolds and Prandtl numbers respectively.

- Energy balance equation of heat transfer fluid:

$$\rho_f V_f c_{p,f} \frac{dT_f}{dt} = h_f A_{abs2-f} (T_{abs2} - T_f) - h_f A_{abs1-f} (T_f - T_{abs1}) - \dot{m} c_{p,f} (T_{out} - T_{in}), \quad (5)$$

where ρ_f , and $c_{p,f}$ denote the density, and specific heat at constant pressure of the fluid, respectively. V_f represents the volume of the channel, A_{abs1-f} and A_{abs2-f} are the contact area between the fluid channel and the upper and lower absorber respectively. $\dot{m}$ correspond to the mass flow rate of the fluid. T_{in} is the temperature at the inlet of the CPV/T system, equal to the temperature at the bottom outlet of the thermal storage tank, while T_{out} is the outlet temperature of the CPV/T, matching the temperature at the top inlet of the thermal storage tank.

- Energy balance equation of bottom layer of absorber substrate:

$$\delta_{abs2} \rho_{abs2} c_{abs2} \frac{dT_{abs2}}{dt} = \frac{\lambda_{abs2}}{\delta_{abs2}} (T_{pv} - T_{abs2}) - h_f (T_{abs2} - T_f), \quad (6)$$

where δ_{abs2} , ρ_{abs2} , c_{abs2} and λ_{abs2} are the thickness, density, specific heat and thermal conductivity of the bottom absorber layer respectively, while T_{abs2} represents the bottom absorber temperature.

- Energy balance equation of PV cells:

$$\begin{aligned} A_{pv} \delta_{pv} \rho_{pv} c_{pv} \frac{dT_{pv}}{dt} = & \alpha_{pv} \eta_{op} K I_b W L - \\ & \frac{\lambda_{abs2}}{\delta_{abs2}} A_{pv} (T_{pv} - T_{abs2}) - \sigma \epsilon_{pv} A_{pv} (T_{pv}^4 - T_{sky}^4) \\ & - U_{cv,pv-amb} A_{pv} (T_{pv} - T_{amb}) - \\ & \gamma_{pv} \eta_{op} K I_b W L - \eta_{op} K I_b W L \eta_e, \quad (7) \end{aligned}$$

where A_{pv} , δ_{pv} , ρ_{pv} , c_{pv} , α_{pv} , ϵ_{pv} and γ_{pv} are the area, thickness, density, specific heat, absorptivity, emissivity and reflectance of photovoltaic system respectively; furthermore, W is the width of collector and L its length; T_{pv} represents the cells temperature, I_b is the direct radiation on the plane of parabolic trough, $U_{cv,pv-amb}$ is convective heat loss coefficient, calculated as (2).

The electrical efficiency of PV cells η_e is expressed with respect to the efficiency in Standard Test Condition (STC), η_{ref} , assuming reference temperature T_{ref} equal to 25 °C and temperature-dependent coefficient β_{pv} reported in Table I.

$$\eta_e = \eta_{ref} [1 - \beta_{pv} (T_{pv} - T_{ref})]. \quad (8)$$

The STC efficiency is reported in Table I. The cell type selected is InGaP/InGaAs/Ge triple-junction, optimized for concentrated sunlight [15].

The optical efficiency η_{op} is described by the following equation [11]:

$$\eta_{op} = \gamma_{PTC} \psi [(1 - A_f \tan \theta) \cos \theta], \quad (9)$$

where, γ_{PTC} is the reflectance of collector, ψ is the intercept factor and A_f a geometric factor calculated as follows:

$$A_f = \frac{\frac{2}{3} W h_p + f W \left(1 + \frac{W^2}{48 f^2}\right)}{A_a}, \quad (10)$$

where h_p and f are the height and the focal length of parabola respectively.

The expression of incident angle modifier, K , is given by [11]

$$K = \cos \theta + 0.000884\theta - 0.000884\theta^2, \quad (11)$$

The radiation incident angle θ is calculated as reported in Section III.

B. Reverse Osmosis

Our study considers a RO unit equipped with an energy recovery device. The performance of this desalination unit is characterized by the RR and the Specific Energy Consumption (SEC), both of which are temperature-dependent.

Agashichev et al. [16] investigated the temperature dependence of the RR. In this work, we derived a regression-based equation describing this relationship, using the data reported by Agashichev et al., considering a feed pressure of 54 bar and a seawater salinity of 40 g/L.

$$RR = 0.0083 \cdot T_{sw} + 0.2472, \quad (12)$$

where T_{sw} is seawater temperature in [°C].

The relation between seawater temperature and SEC is derived by means of regression of values reported in a table by Koutsou et al. [17].

$$SEC = 0.0007 \cdot T_{sw}^2 - 0.0444 \cdot T_{sw} + 3.0616. \quad (13)$$

C. Membrane Distillation

The considered MD units operate in vacuum-assisted air gap operation. The equations that characterize the single module are from Andrés-Mañas et al. [14].

The equations represent the relationship between the permeate flux J , [$\text{Lh}^{-1}\text{m}^{-2}$] and normalized heated seawater temperature at the inlet of evaporation channel of MD, $T_{md,in,n}$, the normalized feed flow rate, $F_{feed,n}$, the normalized feed salinity, $S_{feed,n}$, and the normalized seawater temperature at the inlet of feed channel of MD, $T_{sw,n}$, as well as the relationship between the temperature of seawater pre-heated inside the MD, $T_{md,out}$, and the variables indicated before. Normalization is carried out following the procedure described by [14].

$$\begin{aligned} J = & 0.80 + 0.32 \cdot T_{md,in,n} + 0.56 \cdot F_{feed,n} - 0.15 \cdot T_{sw,n} \\ & - 0.66 \cdot S_{feed,n} + 0.19 \cdot T_{md,in,n} \cdot F_{feed,n} \\ & - 0.11 \cdot T_{md,in,n} \cdot S_{feed,n} - 0.19 \cdot F_{feed,n} \cdot S_{feed,n}, \quad (14) \end{aligned}$$

$$\begin{aligned} T_{md,out} = & 65.11 + 9.16 \cdot T_{md,in,n} - 0.92 \cdot F_{feed,n} \\ & + 0.48 \cdot T_{sw,n} - 1.06 \cdot S_{feed,n} \\ & + 0.15 \cdot T_{sw,n} \cdot F_{feed,n}. \quad (15) \end{aligned}$$

D. Heat Exchanger

The model of heat exchanger is proposed by Gil et al. [18].

The outlet temperature at hot side of heat exchanger, $T_{hx,out}$, and outlet temperature at cold side of heat exchanger, i.e., temperature of RO brine at the inlet of hot side of MD unit, $T_{md,in}$, are calculated with (16) and (17) :

$$T_{hx,out} = T_{hx,in} - \mu_{hx,1} \cdot (T_{hx,in} - T_{md,out}), \quad (16)$$

$$T_{md,in} = T_{md,out} + \mu_{hx,2} \cdot (T_{hx,in} - T_{hx,out}), \quad (17)$$

where, $T_{hx,in}$ is input temperature at hot side of heat exchanger and $\mu_{hx,2}$, $\mu_{hx,1}$ and θ_{hx} are auxiliary factors calculated as follows:

$$\mu_{hx,2} = \frac{\dot{m}_t \cdot c_{p,t}}{\dot{m}_{md} \cdot c_{p,md}}, \quad (18)$$

$$\mu_{hx,1} = \frac{1 - e^{\theta_{hx}}}{1 - \mu_{hx,2} \cdot e^{\theta_{hx}}}. \quad (19)$$

$$\theta_{hx} = U_{hx} A_{hx} \cdot \left(\frac{1}{\dot{m}_t \cdot c_{p,t}} - \frac{1}{\dot{m}_{md} \cdot c_{p,md}} \right), \quad (20)$$

where $\dot{m}_t$ and $c_{p,t}$ are the mass flow rate and specific heat capacity of fluid at the hot side of heat exchanger, while $\dot{m}_{md}$ and $c_{p,md}$ are related to cold side of heat exchanger, i.e., to the fluid at the inlet of MD evaporation channel; U_{hx} [W/m²K] and A_{hx} [m²] are heat transfer coefficient and surface area of heat exchanger respectively.

E. Heat Storage Tank

The heat storage tank is modeled according to equations presented by Andrés-Mañas et al [7]. The heat storage tank is modeled dividing it into two sections, and an energy balance is applied in each of these sections.

$$\begin{aligned} \frac{\rho_f \cdot V_{TES}}{2} \cdot \frac{dT_{t1}}{dt} = & \dot{m}_s \cdot (T_{out} - T_{t1}) \\ & + \dot{m}_p \cdot (1 - vp) \cdot (T_{t2} - T_{t1}) \\ & - \frac{UA_1 \cdot (T_{t1} - T_{amb})}{c_{p,f}}, \end{aligned} \quad (21)$$

$$\begin{aligned} \frac{\rho_f \cdot V_{TES}}{2} \cdot \frac{dT_{t2}}{dt} = & \dot{m}_s \cdot (T_{t1} - T_{t2}) \\ & + \dot{m}_p \cdot (1 - vp) \cdot (T_{hx,out} - T_{t2}) \\ & - \frac{UA_2 \cdot (T_{t2} - T_{amb})}{c_{p,f}}. \end{aligned} \quad (22)$$

Where V_{TES} is the tank volume; $\dot{m}_s$ and $\dot{m}_p$ are the mass flow rates from the solar collectors to the tank and from the three-way valve to the heat exchangers, respectively. T_{out} is the outlet temperature of the fluid from the solar collectors. T_{t1} and T_{t2} represent the temperatures at the top and bottom of the tank. UA_1 and UA_2 are the thermal loss coefficients at the top and bottom of the tank, respectively. vp denotes the position of the 3-way mixing valve between the heat storage tank and the heat exchanger (with 1 indicating full circulation and 0 indicating no recirculation).

III. EXPERIMENTAL EVALUATION

The system is analyzed under real weather conditions in Almería (Spain) over a one-year period. This allows for the estimation of annual water production and recovery ratio, as well as the calculation of the LCOW index. Weather data from the year 2023 are considered and obtained from PV-GIS [19].

A. System assumption

The CPV/T system is designed to supply membrane distillation with enough thermal energy to operate for an average of 10 hours per day in July, with a nominal feed flow rate of 10 m³/h. The RO and MD units operate synchronously, allowing the MD system to treat the entire volume of brine produced by the RO process.

However, sizing with thermal purposes leads to an overproduction of electrical energy, which can be sold to the electrical grid. Our analysis accounts for the variability in seawater temperature. To this end, monthly average seawater temperature data are used [20].

The CPV/T systems employ single-axis tracking. The tilt angle β changes in order to minimize the angle of incidence of solar radiation, θ , which is calculated following this trigonometric relation [21]:

$$\begin{aligned} \cos(\theta) = & \sin(\delta) \sin(\phi) \cos(\beta) \\ & - \sin(\delta) \cos(\phi) \sin(\beta) \cos(\gamma) \\ & + \cos(\delta) \cos(\phi) \cos(\beta) \cos(\omega) \\ & + \cos(\delta) \sin(\phi) \sin(\beta) \cos(\gamma) \cos(\omega) \\ & + \cos(\delta) \sin(\beta) \sin(\gamma) \sin(\omega), \end{aligned} \quad (23)$$

where δ is the declination, ϕ is latitude of the site, ω is the hour angle and γ is the azimuth angle of the parabolic trough.

The fluid circulating within the CPV/T system is pressurized water, used to prevent boiling during periods when temperatures exceed 100 °C.

B. Simulation

Simulations of the system were conducted in Python; the differential equations describing the CPV/T units are solved using the `odeint` solver from Python's SciPy library. The time step of the simulation is 1 minute.

The aim of simulation is to obtain the amount of freshwater produced by RO, MD and RO+MD for each month of the year and the yearly recovery ratio of the desalination units.

C. Economic Analysis

The economic analysis involves calculating the Levelized Cost of Water (LCOW) based on a comprehensive evaluation of the system's costs. The cost of each system component is determined using market prices or specific literature references. For instance, the cost of the CPV/T system is estimated at 360.84 USD/m², as reported in [11], while the capital cost of the RO unit is sourced from [22].

The LCOW is defined as the ratio between the system's total net annual cost and the total volume of water produced over one year.

The total net annual cost comprises the sum of annualized capital expenditures and yearly operation and maintenance costs, minus the revenue generated from the sale of excess electricity. The annualized capital cost is calculated by multiplying the total capital cost by the amortization factor a , given by the following expression:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1}, \quad (24)$$

TABLE II
SUMMARY OF SYSTEM COSTS, ECONOMIC PARAMETERS AND
METHODOLOGY TO OBTAIN THE TOTAL NET ANNUAL COST.

Parameter	Value	Note
Components cost C_c	244710.0 USD	$\sum_{i=1}^N C_{ci}$ ^a
Installation cost C_{in}	61177.5 USD	$0.3 \cdot C_c$
Instrumentation cost C_{st}	61177.5 USD	$0.3 \cdot C_c$
Direct capital cost C_{dc}	367064.9 USD	$C_c + C_{in} + C_{st}$
Indirect capital cost C_{ic}	36706.5 USD	$0.1 \cdot C_{dc}$
Total capital cost C_{cap}	403771.4 USD	$C_{dc} + C_{ic}$
Annual interest rate i	0.03	[22]
Plant lifetime n	25	
Amortization factor a	0.057	[22]
Capital cost annualized C_1	23187.7 USD	$a \cdot C_{cap}$
Operation and maintenance cost C_2	4637.5 USD	$0.2 \cdot C_1$
MD membrane replacement cost C_3	1752.3 USD	$0.15 \cdot 90 \cdot A_{md}$ ^b [24]
RO membrane replacement cost C_4	4950 USD	[22]
Total annual cost C_{tot}	34527.6 USD	$\sum_{j=1}^4 C_j$
Revenue from selling electricity R_e	2355.7 USD	$0.0608 \cdot E_{sur}$ ^c
Total net annual cost C_{net}	32171.9 USD	$C_{tot} - R_e$

^a Cost of each system component [USD]

^b MD membrane area [m²]

^c Excess of electricity produced [kWh]

where i is the annual interest rate and n is the system lifetime; these values are reported in Table II. Excess electricity is assumed to be sold to the grid at Spain's current average market rate for electricity production surpluses: 0.0516 €/kWh, equivalent to 0.0608 USD/kWh [23].

A summary of the system costs and economic parameters is provided in Table II.

IV. RESULTS AND DISCUSSION

The amount of water produced by the desalination system is reported in Fig. 3. Water production depends on solar energy availability, which determines the system's operation time. For this reason, production increases during the summer, reaching a maximum in August and a minimum in February. In August the RO production is 642.62 m³ of water while the MD production is 42.17 m³. In February the RO production is 140.56 m³ and MD production is 13.38 m³. This leads to an overall production of 684.79 m³ in August and 153.94 m³ in February.

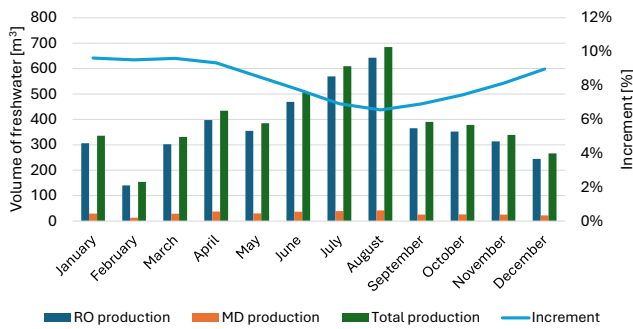


Fig. 3. Water production from RO, MD, and RO-MD systems, with RO-MD increase relative to RO. The primary vertical axis shows water output in m³; the secondary axis shows RO-MD production increase over RO in [%].

TABLE III
ANNUAL RESULTS FOR WATER PRODUCTION, RECOVERY RATIO, AND
ENERGY OUTPUT.

Quantity	Result
Water produced by RO	4458.58 m ³
Water produced by MD	356.37 m ³
Water produced by RO+MD	4814.95 m ³
RO Recovery Ratio	41.06 %
MD Recovery Ratio	5.57 %
RO+MD Recovery Ratio	44.34 %
Electric energy consumption	11.374 MWh
Electric energy generation	50.120 MWh
Excess of electrical energy	38.745 MWh
LCOW	6.68 USD/m ³

The annual increment of water production with respect to RO production due to the presence of MD units is equal to 7.99 % with maximum value in January (9.62 %) and minimum value in August (6.56 %) as shown in Fig. 3. The percentage increase in production decreases in the summer season. This occurs because the rising seawater temperature increases the salinity of RO brine reducing the permeate flux of the MD unit and simultaneously increases the permeate flux of the RO unit. This aspect is further investigated in [14] and [16]. However, the absolute amount of water produced by MD is higher in summer because of the longer operation time of the system due to larger solar energy availability.

The overall yearly results of the proposed system are presented in Table III.

The recovery ratio of the desalination system has increased with respect to the recovery ratio of RO significantly, allowing for a reduction of RO brine production equal to 356.37 m³ per year. Moreover, compared to a standalone MD system, with the same water production, the amount of brine reduced would be equal to 6044.38 m³. These values demonstrate the significant benefits of combining these two desalination technologies.

The electric energy production is 4.41 times the electric energy consumed because the generation system has been sized in order to supply an adequate amount of thermal energy to the desalination system allowing for 10 hours of operation on average in July. This has resulted in an oversizing of the system from an electric point of view. However this allows for a yearly revenue of 2355.7 USD from selling excess electricity to the Spain grid.

The LCOW of 6.68 USD/m³ is notably lower than values reported for comparable standalone renewable-powered systems. For instance, literature values for small scale PV-RO systems range from 11.7 to 15.6 USD/m³ [25], while solar thermal (ST) driven MD systems are reported at 15-18 USD/m³ [3]. Storage systems enable longer system operation and increased water production, but their high costs, 5322.20 USD/unit for electric storage and 17105.30 USD/unit for thermal storage, create opposing effects on total water cost by substantially raising capital investment while improving output. However, the LCOW of the system proposed is still higher than the cost of water produced by conventional desalination process; for instance, Gökçek et al. [26] reported a costs between 1.489

and 1.750 USD/m³ for small-scale RO systems powered only by the electric grid. This is predominantly due to high cost of CPV/T system, of MD units and of storage systems.

V. CONCLUSIONS

This work explores environmentally sustainable methods for freshwater production via desalination, emphasizing the enhancement of the system's RR by reducing brine discharge and relying exclusively on solar energy as power source.

To achieve this, a fully autonomous desalination system powered by solar energy is proposed and evaluated. The system features a CPV/T–RO–MD configuration and is assessed in terms of recovery ratio, water productivity, energy performance, and economic viability. In the proposed setup, MD units are integrated in series with the RO unit to further reduce brine output. The analysis is based on a dynamic simulation of system performance over one year, using real weather data from Almería.

The results indicate that the combined MD and RO system achieves a recovery ratio of 44.34 %, representing a 3.28 percentage point improvement over the RO unit alone. This leads to an increase in water production of 7.99 % compared to an RO-only system. Over the course of a year, the combined system produces a total of 4814.95 m³ of water: 4458.58 m³ from RO and 356.37 m³ from MD. These findings highlight the substantial advantages of coupling the two desalination technologies since the higher brine concentration facilitates its valorization, allowing for higher water production.

Future work will explore systems incorporating multiple MD units in series, aiming to further boost the overall recovery ratio. Additional analysis will also be conducted from exergetic and environmental perspectives.

REFERENCES

- [1] EU Blue Economy Observatory, "Desalination," https://blue-economy-observatory.ec.europa.eu/eu-blue-economy-sectors/desalination_en, 2025, accessed on 24 February 2025.
- [2] E. Jones, M. Qadir, M. T. van Vliet, V. Smakhtin, and S. mu Kang, "The state of desalination and brine production: A global outlook," *Science of The Total Environment*, vol. 657, pp. 1343–1356, 2019.
- [3] B. Tashtoush, W. Alyahya, M. Al Ghadi, J. Al-Omari, and T. Morosuk, "Renewable energy integration in water desalination: State-of-the-art review and comparative analysis," *Applied Energy*, vol. 352, p. 121950, 2023.
- [4] D. Curto, V. Franzitta, and A. Guercio, "A review of the water desalination technologies," *Applied Sciences*, vol. 11, no. 2, 2021.
- [5] A. Prado de Nicolás, Á. Molina-García, J. T. García-Bermejo, and F. Vera-García, "Desalination, minimal and zero liquid discharge powered by renewable energy sources: Current status and future perspectives," *Renewable and Sustainable Energy Reviews*, vol. 187, p. 113733, 2023.
- [6] S. Shalaby, S. W. Sharshir, A. Kabeel, A. Kandeal, H. Abosheishasha, M. Abdelgaied, M. H. Hamed, and N. Yang, "Reverse osmosis desalination systems powered by solar energy: Preheating techniques and brine disposal challenges – a detailed review," *Energy Conversion and Management*, vol. 251, p. 114971, 2022.
- [7] J. Andrés-Mañas, L. Roca, A. Ruiz-Aguirre, F. Acién, J. Gil, and G. Zaragoza, "Application of solar energy to seawater desalination in a pilot system based on vacuum multi-effect membrane distillation," *Applied Energy*, vol. 258, p. 114068, 2020.
- [8] M. Herrando, K. Wang, G. Huang, T. Otanicar, O. B. Mousa, R. A. Agathokleous, Y. Ding, S. Kalogirou, N. Ekins-Daukes, R. A. Taylor, and C. N. Markides, "A review of solar hybrid photovoltaic-thermal (pv-t) collectors and systems," *Progress in Energy and Combustion Science*, vol. 97, p. 101072, 2023.
- [9] B. Anand, R. Shankar, S. Murugavelh, W. Rivera, K. Midhun Prasad, and R. Nagarajan, "A review on solar photovoltaic thermal integrated desalination technologies," *Renewable and Sustainable Energy Reviews*, vol. 141, p. 110787, 2021.
- [10] W. J. Cameron, K. S. Reddy, and T. K. Mallick, "Review of high concentration photovoltaic thermal hybrid systems for highly efficient energy cogeneration," *Renewable and Sustainable Energy Reviews*, vol. 163, p. 112512, 2022.
- [11] M. Mortadi and A. El Fadar, "Novel design of concentrating photovoltaic thermal collector – a comparative analysis with existing configurations," *Energy Conversion and Management*, vol. 268, p. 116016, 2022.
- [12] A. Khouya, "4e assessment of a hybrid ro/med-tvc desalination plant powered by cpv/t systems," *Energy Conversion and Management*, vol. 277, p. 116666, 2023.
- [13] M. Wiesenfarth, J. Went, A. Bösch, A. Dilger, T. Kec, A. Kroll, J. Koschikowski, and A. W. Bett, "Cpv-t mirror dish system combined with water desalination systems," *AIP Conference Proceedings*, vol. 1766, no. 1, p. 020008, 09 2016.
- [14] J. Andrés-Mañas, I. Requena, and G. Zaragoza, "Membrane distillation of high salinity feeds: Steady-state modelling and optimization of a pilot-scale module in vacuum-assisted air gap operation," *Desalination*, vol. 553, p. 116449, 2023.
- [15] K. Rahbar, A. Riasi, H. Khatam Bolouri Sangjoeei, and N. Razmjoo, "Heat recovery of nano-fluid based concentrating photovoltaic thermal (cpv/t) collector with organic rankine cycle," *Energy Conversion and Management*, vol. 179, pp. 373–396, 2019.
- [16] S. P. Agashichev and K. N. Lootahb, "Influence of temperature and permeate recovery on energy consumption of a reverse osmosis system," *Desalination*, vol. 154, no. 3, pp. 253–266, 2003.
- [17] C. Koutsou, E. Kritikos, A. Karabelas, and M. Kostoglou, "Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes," *Desalination*, vol. 476, p. 114213, 2020.
- [18] J. D. Gil, J. Álvarez, L. Roca, J. Sánchez-Molina, M. Berenguel, and F. Rodríguez, "Optimal thermal energy management of a distributed energy system comprising a solar membrane distillation plant and a greenhouse," *Energy Conversion and Management*, vol. 198, p. 111791, 2019.
- [19] European Commission, "Photovoltaic Geographical Information System (PVGIS)," https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en, 2023, accessed on 23 March 2025.
- [20] SeaTemperature.info, "Water temperature in Almería," <https://seatemperature.info/spain/almeria-water-temperature.html>, 2025, accessed on 01 July 2025.
- [21] W. A. Beckman, N. Blair, and J. A. Duffie, *Solar Engineering of Thermal Processes, Photovoltaics and Wind, Fifth Edition*. Wiley, 2021.
- [22] A. K. Elfaqi and S. O. Belhaj, "Economic evaluation of swro desalination plants using erd powered by off-grid pv system," in *2021 IEEE 1st International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering MI-STA*, 2021, pp. 458–462.
- [23] Todo Luz y Gas, "Precio del kWh del excedente de energía por autoconsumo hora a hora en el mercado regulado," <https://www.todoluzygases.es/autoconsumo/precios-excedentes-de-autoconsumo>, 2025, accessed on 17 June 2025.
- [24] F. Macedonio, E. Curcio, and E. Drioli, "Integrated membrane systems for seawater desalination: energetic and exergetic analysis, economic evaluation, experimental study," *Desalination*, vol. 203, no. 1-3, pp. 260–276, 2007.
- [25] M. A. Al-Obaidi, R. H. A. Zubo, F. L. Rashid, H. J. Dakkama, R. Abd-Alhameed, and I. M. Mujtaba, "Evaluation of solar energy powered seawater desalination processes: A review," *Energies*, vol. 15, no. 18, 2022. [Online]. Available: <https://www.mdpi.com/1996-1073/15/18/6562>
- [26] M. Gökçek and Öznur Begüm Gökçek, "Technical and economic evaluation of freshwater production from a wind-powered small-scale seawater reverse osmosis system (wp-swro)," *Desalination*, vol. 381, pp. 47–57, 2016.