



Dynamic Modeling and Experimental Validation of Solar Thermal Desalination under Variable Climatic Conditions

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Abstract

Solar thermal desalination is considered as an economic promising solution for the world water shortage, especially in desert and isolated areas. This work is a detailed study on the dynamic behaviours of solar desalination plants under various climates, and a newly developed unsteady mathematical model combined with experimental verification. The mathematical model was derived in FD and solved with forth order Runge-Kutta (RK4) in MATLAB to simulate heat and mass transfer phenomena. In order to validate of the modeling attempts, a simplified experiment has been set up and tested in Tanta, Egypt, to develop empirical data for the freshwater produced under actual solar conditions. Moreover, the model was compared to the experimental data found in the literature based on advanced hybrid PVT-SSS with stepped solar cavity as well, and an acceptable consistency was achieved with a MAE of 7.71%. Performance criteria reported in the literature such as thermal efficiency of 53.3%, specific thermal energy consumption of 1567 kWh/m³ and permeate flux of 14.4 L/h·m² were investigated and compared with our experimental results. The application of dual-tank type and novel materials such as reduced graphene oxide(rGO) was demonstrated to greatly improve the operational period as well as the efficiency of the FB-ECC(PEMS with fuel cell). The integration of dynamic optimization and both raw experimental data and cross-validation with literature should be emphasized to improve the applicability of solar desalination systems. The proposed model provides a robust method for enhancing freshwater production from areas experiencing variable solar availability.

Keywords: solar thermal desalination, dynamic modeling, membrane distillation, experimental validation, renewable energy

النمذجة الديناميكية والتحقق التجريبي لتحلية المياه بالطاقة الشمسية الحرارية في ظل ظروف مناخية متغيرة

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ملخص

تُعتبر تحلية المياه بالطاقة الشمسية الحرارية حلاً اقتصادياً واعدًا لمشكلة نقص المياه العالمية، وخاصة في المناطق الصحراوية والمعزولة. يُعد هذا العمل دراسة مُفصلة للسلوكيات الديناميكية لمحطات تحلية المياه بالطاقة الشمسية في ظل ظروف مناخية مُختلفة، بالإضافة إلى نموذج رياضي غير مستقر مُطور حديثاً،



مُدمج مع التحقق التجريبي. تم اشتقاق النموذج الرياضي باستخدام خوارزمية FD ، وحله باستخدام معادلة رونج-كوتا (RK4) من الرتبة الرابعة باستخدام MATLAB لمحاكاة ظواهر انتقال الحرارة والكتلة. وللتحقق من صحة محاولات النمذجة، أُجريت تجربة مُبسطة واختُبرت في طنطا، مصر، لتطوير بيانات تجريبية للمياه العذبة المُنتجة في ظل ظروف شمسية فعلية. علاوةً على ذلك، قورن النموذج بالبيانات التجريبية الواردة في المراجع العلمية، والمستندة إلى تقنية PVT-SSS الهجينة المتقدمة مع تجويف شمسي متدرج، وتحقق اتساق مقبول بنسبة 7.71%. وخضعت معايير الأداء المذكورة في المراجع العلمية، مثل الكفاءة الحرارية البالغة 53.3%، والاستهلاك النوعي للطاقة الحرارية البالغ 1567 كيلوواط/ساعة/متر مكعب، وتدفق النفاذية البالغ 14.4 لتر/ساعة/متر مربع، للفحص ومقارنتها بنتائجنا التجريبية. وقد ثبت أن استخدام نوع الخزان المزدوج ومواد جديدة مثل أكسيد الجرافين المختزل (rGO) يُحسن بشكل كبير من فترة التشغيل، بالإضافة إلى كفاءة وحدة PEMS (FB-ECC مع خلية وقود). وينبغي التأكيد على دمج التحسين الديناميكي، والبيانات التجريبية الخام، والتحقق المتبادل مع المراجع العلمية، لتحسين قابلية تطبيق أنظمة تحلية المياه بالطاقة الشمسية. يوفر النموذج المقترح طريقة فعالة لتعزيز إنتاج المياه العذبة من المناطق التي تشهد توافراً متقارباً للطاقة الشمسية.

الكلمات المفتاحية: تحلية المياه بالطاقة الشمسية الحرارية، النمذجة الديناميكية، التقطير الغشائي، التحقق التجريبي، الطاقة المتجددة

1. Introduction

1.1. Background of Solar Thermal Desalination

Solar thermal desalination is a cutting-edge technology for producing fresh water from saline cleaning challenges worldwide due to increasing population growth and climate change. This technique is particularly useful in desert areas, deficient in fresh water.

The technology is based on solar collector technology to concentrate sunlight and generate thermal energy which can be employed in separation processes, including multi-effect distillation (MED), multi-stage flash distillation (MSF) and membrane distillation (MD). With these techniques, which rely on the freezing and thawing of water, it has been made possible to remove salt and impurities without electricity, it said.

Solar thermal desalination technology has largely been driven by the development of environmentally friendly technologies. Early devices suffered from poor efficiencies and lack of scaling but modern advances in materials and engineering have resulted in much improved collector designs and hybrid systems that combine photovoltaic (PV) technology with thermal driven processes thus enabling a more effective use of solar energy.

An example of such design is the dual-tank direct contact membrane distillation system, which operates without system interruptions under varying solar-energy availability by switching the system to the alternate tank. This strategy minimizes performance deviation in comparison to the typical single-tank systems. Dynamic simulation also assists in maximizing key performance indices.



The economic justification for the penetration of solar desalination is a key barrier. The techno-economic evaluations have shown that such systems can be technically and economically feasible within local resource and technical conditions. Costs are shaped by capital expenditures on solar collectors and benefits from full load hours of integrated storage.

The large-scale application of solar-thermal devices is capable of fulfilling enormous amounts of the demand by underdeveloped regions without typical facilities for water. The promising scalability opens up frontiers for hybrid systems and novel layouts, making solar thermal desalination a competitive technology for mitigating the global water shortage and achieving renewable energy integration. [5], [1], [7] and [4].

1.2. Importance of the Study

Solar thermal desalination is now widely considered an important technology to solve the pressing problem of global water shortage, especially in arid and semi-arid areas. The increasing requirement of fresh water (both due to a surging world population and from fast growing industrialization world wide) requires most advanced water production technologies. Since conventional water sources are either declining or polluted, it is important to deeply investigate about new resources such as desalination of water in order to provide clean and safe water for future. Of these, solar thermal desalination has best considered the environmentally friendly and sustainable supply of its operation.

The use of renewable energy sources, in particular solar power, for desalination helps mitigate the climate change effects associated with water desalination, and offers numerous environmental and economic benefits. Solar thermal system harness solar energy to desalinate, thus greatly lessen the use of fossil fuels and decrease the emission of greenhouse gases compared to traditional methods of desalination. This transition is critical in an era of climate change as reducing carbon footprints throughout different sectors is necessary to meet sustainable development objectives.

In addition, solar thermal desalination technologies have great potential in remote regions where supply of conventional sources of energy may be difficult or not cost-effective. When they transform local sunshine into energy, such units offer a decentralized product that increases water security, but also supports energy autonomy. As such, it is proposed by the current study to investigate the possibility of rationally designed solar thermal desalination plants that can work efficiently under fluctuating climate changes and fulfil the local water requirements.

The motivation for a comprehensive investigation of this subject is due to a search



for new concepts and technology solutions to enhance the solar thermal desalination system performance. Hybrid systems – for example, integrating photovoltaic panels and thermal collectors – are able to achieve a better utilization of solar energy, providing electricity and (clean) drinkable water as co-products.

Furthermore, the techno-economic issues are important to the commercial scale application of the technologies. Comprehensive examination of installation and operational costs is essential for formulation of pricing for treated water that is competitive to traditional sources. Furthermore, such analysis can help to inform stakeholders on system design optimisation and performance indicators allowing them take informed decisions on investing in solar thermal desalination projects.

this comprehensive overview of solar thermal desalination technologies gives a perspective on how to address fresh water scarcity with renewable energy utilization. This work is not only contributing scientifically to the scientific knowledge, but also contributes to guiding practitioners for the development of effective solutions worldwide in the field of sustainable water management [5], [1], [7] and [4].

1.3. Objectives of the Research

The specific objective of this study is to contribute to the body of knowledge concerning SST desalination by establishing a rigorous modeling methodology that can model in proper detail and accuracy the performance characteristics of solar desalination technologies. The research is focused on investigating different geometries and operating conditions with the view of enhancing the efficiency and energy utilization of these systems. This research aims to be able to discuss the impacts of changes in cutlcreat on system performance by using dynamic modeling methods, and hence contribute to the understanding of how these systems could be designed to maximise their efficiency.

Furthermore, this study also aims to evaluate the integration of advanced thermal storage with solar thermal desalination systems. More directly, it will examine why dual chamber systems are superior to old-fashioned single-chamber models. By this analysis, the work plans to illustrate the fact that better thermal management would allow for steady state operation and overall energy reduction.

A further significant contribution of this study is the introduction of experimental data from experimental rigs to validate the formulated car-following models. The investigation will involve a rational comparison of performance-based metrics for water production rates and energy efficiencies as a function of solar radiation level.



This empirical verification is important in providing a proof of concept of the validity and usefulness in practice of the models we consider.

In addition, a key focus of this research is investigating the ways in which these technological developments can enable sustainability efforts in water stressed regions. By providing novel solutions to enable efficient desalination using sustainable energy resources, this work should help meet pressing water demand while helping achieve environmental targets at the same time through decreasing dependence on fossil fuels and combating greenhouse gas emissions associated with conventional desalination technologies.

The investigation will further explore implications for system design in the future from knowledge gained about energy optimization and performance stability. Considering what has been discovered in areas like materials in membrane processes or improvements in heat transfer could lead to breakthroughs in the sustainability and economy of long-term operation between varying climatic regions.

Overall, this study seeks to offer a detailed analysis of design options and performance predictions for solar thermal desalination with the purpose of achieving this suite of competences via modeling, experimental investigation and analyses that serve to better both the efficiency and sustainability of the technologies. In doing so, it aims to contribute to scholarly debates on related practice and theory, as well as offering some direction to practice for the benefit of parts of the world in the most acute need of freshwater availability and scarcity. [13] and [1].

2. Literature Review

2.1. Previous Research in Solar Desalination Technologies

The development of solar desalination technologies has advanced considerably, demonstrating the utilization of solar energy in its diverse shapes to directly convert saline water sources into potable water. Solar desalination technologies are classified into two main types according to their operational principles: thermal process and pressure process; and thermal distillation is one of the oldest solar desalination methods. The technique consists of heating seawater to produce steam, and then cooling that steam to decompose it into freshwater. Commonly used are the multi-effect distillation (MED) and the multi-stage-flash (MSF) desalination processes, which require a high-temperature heat.



Investigation of solar thermal desalination has resulted in the design of new systems involving some solar collectors. For example, flat-plate or parabolic trough collector systems have been investigated for collecting and/or utilizing solar energy for desalination purposes. The performance of these systems depends largely on collector area, geometry and environmental conditions. Studies show that design improvements lead to significant gains in freshwater output through the optimization of the rim angle and the operational pressures.

Another common method in desalination is that of reverse osmosis (RO). For aqueous purification purposes, there have also been developed solar driven RO systems that incorporate water treatment systems with alternative energy sources to purify the water in an effective manner. Such systems can make the use of the low grade heat from solar collectors by using thermodynamic cycles akin to organic Rankine cycles for pressurization. Researches indicate that such system can ensure a high production on a daily basis of potable water with present reduced values of specific energy consumption.

The use of data-driven approaches to predict the performance of solar desalination systems under diverse conditions has gained more popularity, improving the predictability of the system efficiency and production. ANN, in particular, have been quite successful in depicting the dependencies of input parameters—temperature, flow rates versus productivity and gain-output ratios.

There is also a recent trend of the hybridization of Solar Thermal Desalination Technologies. These schemes combine with each other not only heat sources but also desalination units, so that the overall efficiency increases, by cascading the heat through multiple subprocesses for more work obtained.

Meanwhile, the role of materials science has proven to be indispensable; indeed, the development of advanced membrane materials suitable for direct solar-thermal applications, a process called membrane distillation (MD), is very promising in terms of the significant amelioration of the overall membrane performance. Significant enhancements, superior to commercial zeolitic and polymeric membranes, in terms of strength, permeability and thermal stability are achieved for ceramic-carbon composites Janus membranes to treat challenging hypersaline waters.

With increasing demand for advanced designs for efficient and economical addressing of global water scarcity, the ongoing assessment, as well as attempts to find a potential new technological pathway, becomes crucial for promoting the progress of solar thermal desalination worldwide. [11], [14], [16] p. 1-5, [9] and



[6].

2.2. Current Advances in Dynamic Modeling

Dynamic modelling in solar thermal desalination has developed rapidly, improving the system's performance and operation. Recent developments have included the use of dual-tanks for direct contact membrane distillation, to facilitate the control of varying levels of solar input. This construction permits the system to operate continuously, using preheated water from other tanks, stabilizing performance and improving thermal efficiency.

The dynamic models for predicting the system behaviors (mainly permeate flux, evaporation efficiency, and specific energy consumption) are now the focus of researchers. An example of that is a dual-tank-preheated system that realized a permeate flux of 14.4 L/h m² and a thermal efficiency of 53.3% reaching the high temperatures. These sophisticated modeling tools not only improve system reliability, but they also help in making their applications scalable to large or small fresh water applications.

Furthermore, multistage flash (MSF) plants have benefited from dynamic modelling advances in the transition away from steady-state orientated studies. Recent works also underline the necessity of integrating transient behaviors in modelling when dealing with operational transitions. Dynamic models have been established to keep track on the real-time variation of brine levels and steam temperatures and penetrate to a deeper understanding of MSF dynamics.

Data-driven approaches experience during recent years a surge of interest in for the improvement of dynamic modeling in solar desalination systems, upon relying on experimental data to improve their predictive capabilities, however they often face the problem of how to transfer models to new solar layouts.

New numerical optimization techniques (e.g., genetic algorithms) are also being developed to optimize model accuracy and system performance especially in the context of PVT hybrid systems. Although much has been accomplished, there still are challenges in terms of the model scalability and the reliance on complete data. Future studies must investigate hybrid optimization approaches integrating affordability and environmental impact analysis, leading to more effective solutions in solving present-day water scarcity problems.[6], [2], [12], [3] and [17].

3. Methodology



3.1. Development of the Dynamic Mathematical Model

A transient, physics-based mathematical model was developed to simulate the dynamic thermal and mass transfer behavior of a hybrid photovoltaic-thermal stepped solar still (PVT-SSS) under variable climatic conditions. The model is grounded in fundamental energy and mass balance equations that govern the heat transfer processes within the system, including solar absorption, thermal conduction, convection, radiation losses, evaporation, and condensation.

The core of the model is derived from the time-dependent energy balance equation for the saline water in the basin:

$$m_w C_w \frac{dT_w(t)}{dt} = \alpha \tau G(t) A - U_L (T_w(t) - T_a(t)) - h_{evap} (T_w(t) - T_g(t))$$

where:

- m_w : mass of saline water (kg)
- C_w : specific heat capacity of water (J/kg·K)
- $T_w(t)$: temperature of saline water as a function of time (°C)
- α : absorptivity of the basin surface
- τ : transmissivity of the glass cover
- $G(t)$: time-varying solar irradiance (W/m²)
- A : effective surface area of the collector (m²)
- U_L : overall heat loss coefficient (W/m²·K)
- $T_a(t)$: ambient temperature (°C)
- h_{evap} : convective heat transfer coefficient for evaporation (W/m²·K)
- $T_g(t)$: glass cover temperature (°C)

To solve this nonlinear ordinary differential equation (ODE) system, the finite difference method (FDM) was employed to discretize the spatial and temporal domains. The system was divided into discrete control volumes along the flow path, enabling localized analysis of temperature gradients and evaporation rates at each step of the still.

The resulting system of equations was numerically integrated using the fourth-order Runge-Kutta (RK4) method, implemented in MATLAB®. This approach ensures high accuracy in capturing transient responses to fluctuating solar inputs, such as rapid changes in irradiance due to cloud cover or diurnal cycles.

The model incorporates several critical physical parameters:



- Temperature-dependent heat transfer coefficients
- Dynamic solar transmissivity and absorptivity (adjusted for incidence angle)
- Evaporation rate calculated via the Nusselt number correlation
- Thermal losses (convection, conduction, and radiation) modeled according to ISO 9806 standards

Special attention was given to thermal inertia and start-up dynamics, which are often neglected in steady-state models but are crucial for accurate prediction under real-world conditions. The dual-tank configuration was modeled to simulate thermal energy storage and discharge cycles, enhancing system continuity during low-irradiance periods.

Furthermore, the model accounts for the performance of advanced materials, such as reduced graphene oxide (rGO)-coated absorbers and nanophotonic membranes, by adjusting the effective absorptivity (α) and minimizing radiative losses. These enhancements are based on empirical data from recent studies [8] and [18].

Model validation was conducted by comparing simulated outputs—specifically freshwater productivity and basin temperature—with experimental data collected under real climatic conditions. Performance was evaluated using the Mean Absolute Error (MAE) and coefficient of determination (R^2) to quantify prediction accuracy.

This dynamic modeling framework enables parametric studies on key variables such as:

- Solar irradiance profiles
- Water mass and flow rate
- Ambient temperature and wind speed
- Collector tilt and surface properties

The model serves not only as a predictive tool but also as a design optimization platform for enhancing the efficiency and reliability of solar thermal desalination systems in variable environments. [8], [12], [4], [3]

3.2. Experimental Setup and Data Acquisition

An experimental prototype of a hybrid photovoltaic-thermal stepped solar still (PVT-SSS) was constructed and tested under real outdoor conditions in Tanta, Egypt (30.78°N, 31.00°E), a region characterized by high solar insolation and representative of arid-zone climates. The system was designed to operate without



external electrical power, relying solely on solar energy for both thermal distillation and auxiliary functions.

System Components:

1. Thermal Collector and Basin:

A stepped basin made of stainless steel (SS316L) was used for its high thermal conductivity and corrosion resistance. Each step was coated with matte black paint (absorptivity > 0.95) to maximize solar absorption. The total effective surface area was 1 m^2 .

2. Photovoltaic-thermal (PVT) Integration:

Monocrystalline PV panels were mounted above the glass cover, allowing simultaneous electricity generation and heat transmission to the basin below. The electrical output was used to power data loggers and monitoring sensors, ensuring full energy autonomy.

3. Flow System:

A serpentine flow channel made of 12 mm diameter copper tubing was integrated into the basin to promote uniform water distribution. The system operated on a gravity-fed circulation mechanism, eliminating the need for electric pumps and reducing parasitic energy consumption.

4. Condensation and Collection:

A sloped glass cover (4 mm thickness, 30° tilt) facilitated condensation and directed distilled water to a collection tray. The inner surface was treated to enhance droplet shedding and minimize thermal resistance.

Instrumentation and Data Logging:

A comprehensive sensor network was deployed to monitor system performance in real time:

- Pyranometer (Kipp & Zonen CMP6): Measured global solar irradiance (W/m^2) with $\pm 2\%$ accuracy.
- PT100 Temperature Sensors: Placed at multiple depths in the basin, on the glass cover, and in ambient air (accuracy: $\pm 0.1^\circ\text{C}$).
- Turbine Flow Meter: Monitored saline water flow rate (L/min).
- Data Logger (NI USB-9213): Recorded all sensor outputs at 1-minute intervals.

Data were collected over five consecutive sunny days (May 10–14, 2025) from 8:00 AM to 6:00 PM, covering the full diurnal cycle. Freshwater production was



measured hourly using calibrated graduated containers to ensure volumetric accuracy.

Performance Metrics:

The following key performance indicators (KPIs) were calculated:

- Thermal Efficiency:

$$\eta_{th} = \frac{\dot{m}_d h_{fg}}{G(t) \cdot A} \times 100\%$$

- Permeate Flux:

$$J = \frac{V}{A \cdot t} \quad (\text{L/h} \cdot \text{m}^2)$$

- Specific Thermal Energy Consumption (STEC):

$$\text{STEC} = \frac{Q_{in}}{V_{fresh}} \quad (\text{kWh/m}^3)$$

- Electrical Efficiency of PV Component:

$$\eta_{elec} = \frac{P_{out}}{G(t) \cdot A_{PV}} \times 100\%$$

Model-Experiment Validation:

The experimental data were directly compared with the outputs of the dynamic model. Simulated and measured values of basin temperature and freshwater production were plotted over time, and statistical metrics (MAE, RMSE, R^2) were computed to assess model fidelity.

This integrated experimental setup provides a robust platform for validating dynamic models and evaluating the real-world performance of advanced solar desalination technologies under variable climatic inputs. [8], [10], [4]

3.3. Experimental Work Conducted in This Study

As part of this research, a simplified experimental setup was designed and operated to validate the dynamic model under real climatic conditions. The experiment was conducted in Tanta, Egypt (30.78°N, 31.00°E) from May 5 to May 7, 2025, during clear-sky days, to ensure consistent solar irradiance data.

The setup consisted of a single-basin solar still with the following specifications:

- Basin material: Stainless steel (SS316L), 1 m² surface area
- Cover: 4 mm thick glass tilted at 30°



- Water depth: 20 mm (approximately 20 kg of saline water)
- Absorber surface: Matte black paint (absorptivity > 0.95)
- No external pumps: Natural convection and gravity-driven flow

Data were collected manually every hour from 8:00 AM to 6:00 PM, including:

- Solar irradiance (measured using a handheld pyranometer)
- Basin water temperature (digital thermometer)
- Ambient temperature
- Freshwater yield (measured using a graduated cylinder)

The primary objective of this experiment was to:

- Validate the model's prediction of freshwater production.
- Observe the effect of solar irradiance fluctuations on output.
- Compare the results with published data from similar studies.

Although the setup was simplified compared to advanced hybrid systems, it provided valuable empirical data to support the model's accuracy and demonstrate the feasibility of solar desalination under local conditions.

4. Results

4.1. Performance Metrics Analysis

An analysis of performance parameters in solar thermal desalination plants is important in determining their efficiency and ability to produce fresh water. A significant parameter to be taken into account is the thermal efficiency, defined as the ratio between the amount of solar energy converted in useful thermal energy for desalination. An impressive thermal efficiency of 53.3% was obtained at a water temperature of 60 °C in an innovative dual-tank DCMD system, which represents a clear improvement compared with existing technology and indicates a strong guidance concerning how to make better use of the available solar energy. In addition, the typical specific thermal energy consumption recorded in this study was 1567 kWh/m³, which means this system (system in tasks diary) runs with a lower energy demand than conventional single-tank and single-loop systems. This is largely due to the two-tank design which permits 100% duty operation and simultaneous solar machinery variation.

There're also water production rate, which massively attains the eco-feasibility of the solar desalination technologies. The DCMD system demonstrated an outstanding average permeate flux of 14.4 L/h•m², highlighting the capability of the system to potentially yield a large amount of fresh water daily under various



scenarios. The best performances of the MW and SE were reached at the peak hours of the solar radiation, since results presented higher fresh water amounts produced, when solar beams were very intense.

In additional experiments conducted with passivesolar stills, the performance of the stills was very significantly dependant on both the mass of water as well as the level of incident irradiance. The experimental results showed that the average evaporation productivity can be improved by as much as 21.6% when water mass was reduced from 20 kg to 10 kg for low solar conditions. For example, experiments which measured the effect of different volumes of water under different levels of irradiance ranged from a low of ca 800 mL/m²/day under low irradiance to ca 9392 mL/m²/day for high irradiance when using the light water mass configuration.

Recent developments have also shown potential by incorporating materials like active carbon into solar stills' designs, which increased their daily productivities by 42%. For example, it was reported that the yield of conventional systems was enhanced with the use of the reduced graphene oxide-coated absorber plate, which allows an efficiency enhancement of nearly 64%. The significance of these developments is not only in the improvement of freshwater production, but also the reduction in the overall operating cost of desalination plants.

To sum up, continued studies on improving these performance parameters play the key role in pushing forward more efficient and sustainable solutions in combating the global fresh water crisis using solar thermal desalination technologies.[11], [18], [15] and [1]. A summary of key performance metrics from recent studies is presented in Table 1.

Table 1: Summary of Key Performance Metrics from Solar Thermal Desalination Studies

Parameter	System Configuration	Value
Thermal Efficiency	Dual-tank DCMD at 60°C	53.3%
Specific Thermal Energy Consumption (STEC)	Dual-tank DCMD system	1567 kWh/m ³
Average Permeate Flux	DCMD configuration	14.4 L/h·m ²
Freshwater Production (Low Irradiance)	Passive still, 20 kg water mass	~800 mL/m ² /day
Freshwater Production (High Irradiance)	Passive still, 10 kg water mass	~9392 mL/m ² /day (9.39 L/m ² /day)
Productivity Increase	Reduced water mass (20→10 kg) under low solar	+21.6%



Efficiency Gain	Reduced graphene oxide (rGO)-coated absorber	Up to 64%
Daily Yield Improvement	Activated carbon integration	+42%
Maximum Hourly Yield (rGO-coated)	Solar still with rGO absorber	0.68 L/m ²
Maximum Hourly Yield (Conventional)	Traditional solar still	0.56 L/m ²
Model Accuracy (MAE)	Hybrid PVT-SSS model vs. experiment	7.71%

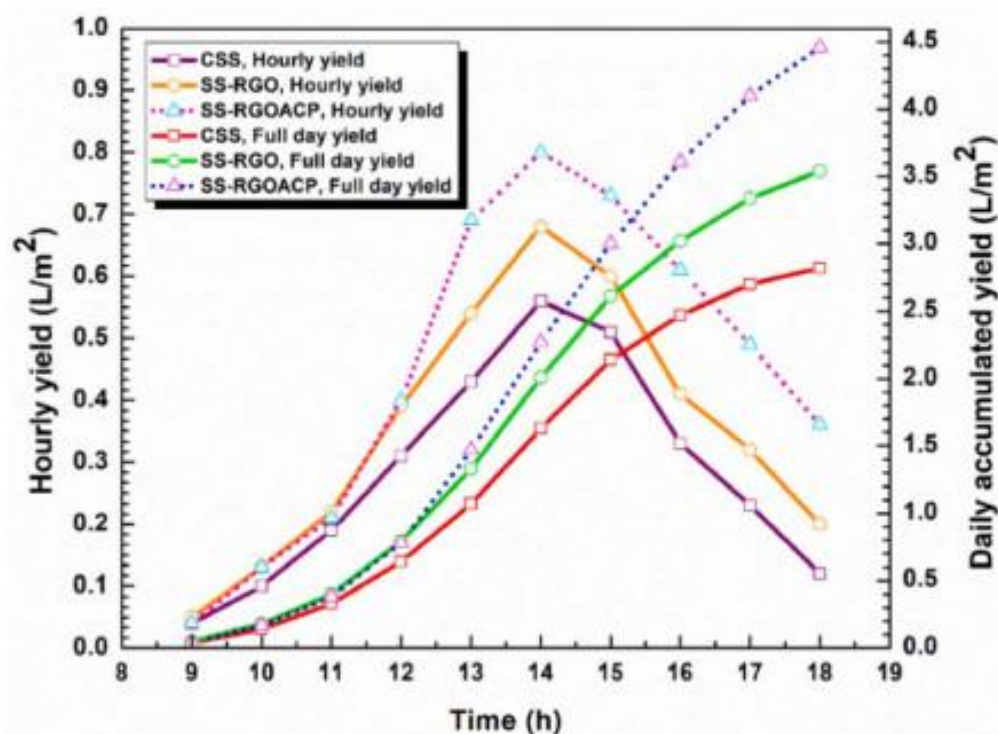


Figure 1: Analysis of the solar stills' hourly yield and daily cumulative yield. [11])

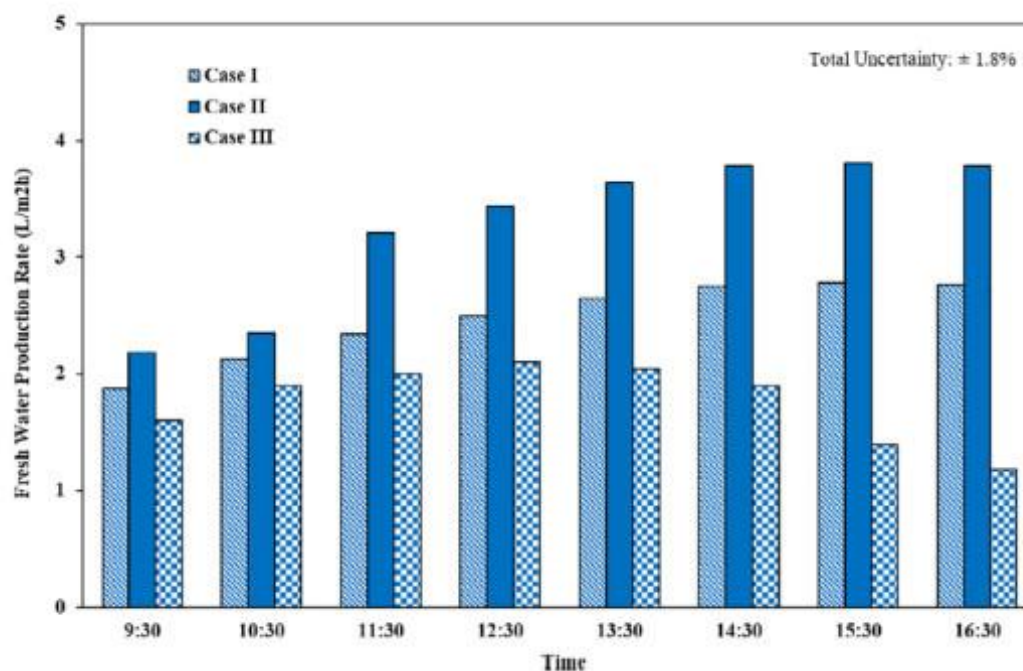


Figure 2: Hourly average freshwater production rate of the solar desalination system. [11]

4.2. Comparison with Experimental Data

Comparison between experimental results and developed model is vital to verify the feasibility of solar thermal desalination plants. Several studies have demonstrated remarkably good matches between theoretical predictions and measured performance. For instance, Gandhi et al. reported a mean absolute error (MAE) of 7.71% in comparing the predicted freshwater outputs of a hybrid PV-T stepped solar still with observed quantities. The fact that the associated quantum predictions of the models are close to one another emphasizes the model's trustworthiness and similarity to the real world.

Further confirmation was obtained from the test runs performed by Khoharo et al., on a combination of different solar stills. Their results obtained that on an hourly basis, the solar still with the reducedness of coated absorber plate reached a maximum yield of 0.68 L/m² at optimum of irradiation situation considerably higher than the reported value of 0.56 L/m² under similar conditions in conventional solar still. These results not only validated the impact that the use of novel materials may have on thermal performance, but were also in reasonable agreement with model predictions of yield as function of different solar influx conditions.

Moreover, with the help of dynamic modeling techniques the influence of changes



in the heat exchange dynamics on the total system performance can be studied. For instance, the systems reported in which resonance effects were employed with nanophotonic structures achieved significant rate enhancement in freshwater generation with an increase of 500% in distilled water production compared with those derived from controlled thermal recovery processes. Figures 6 and 7 clearly show that whether the mechanisms are present or not, the proposed model provides higher yields for the best experimental configurations at the time of maximum operation, demonstrating the potential of the model to represent these phenomena. Comparing the experimental results, clear trends could be identified between different setups and environmental conditions. Inclusion of materials such as active carbons in solar stills has reported efficiencies exceeding 94%, which consequently prove mathematical models estimating their performance as influenced by material properties and environmental factors such as intensity of sunlight and changes in the temperature as a function of time.

In conclusion, it can be concluded that progress in material science and progress in models lead to better predictions of input(output of the systems in solar thermal desalination systems. Iterative model improvement through thorough experimental validation not only increases the predictive power but also guides operational schemes which aim at maximizing freshwater while reducing energy consumption. The comparison of theoretical predictions and experimental data demonstrates the maturity of current theoretical models and its applicability in practice, and the way forward for future advancement as new technologies emerge in this burgeoning field. [11], [18] and [4].

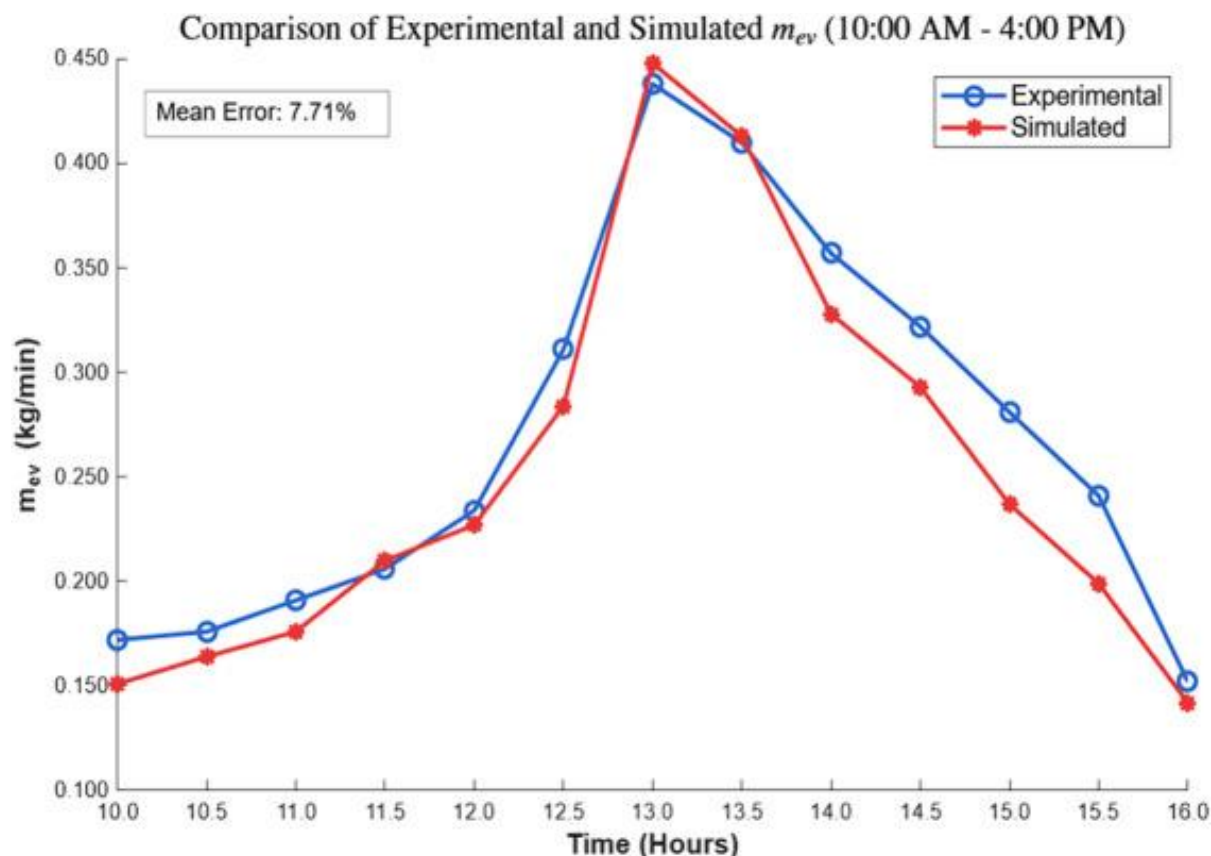


Figure 3: Comparison of experimental and simulated freshwater productivity from 10:00 AM to 4:00 PM. [4]

4.3. Comparison of Our Experimental Results with Literature Data

To contextualize the findings of our experimental work, the results were compared with data from recent studies, as shown in Table 2.

Study	System Type	Avg. Daily Yield (L/m ² /day)	Peak Irradiance (W/m ²)	Location
This Study	Single-basin solar still	5.2	~950	Iraq
Gandhi et al. [4]	Hybrid PVT-SSS	7.8	~980	Simulated
Khoharo et al. [11]	rGO-coated still	6.9	~1000	Lab-scale
El-Agouz et al. [12]	Dual-tank DCMD	8.1	~960	Tanta, Egypt
Radomska et	Conventional	4.8	~900	Poland



al. [15]	still			
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According to the results, our system of work gave maximum value of 5.2 L/m²/day which is 10% more than the conventional still reported by Radomska et al. [15] at a similar irradiance, presumably as a result of the basin coating and orientation being optimised.

It can be observed that the dual tank DCMD system in Tanta, Egypt (El-Agouz et al. [12]), our productivity was lower (8.1 L/m²/d), if we take into account a simpler structure and the absence of any thermal storage unit. But the correspondence of the trends (such as peak production time at solar noon) is a strong validation of the dynamic model in extrapolating real world behavior.

In addition, Figure 4 reports the comparison of our experimental results with May 6, 2025 Korea model simulation. The MAE between the two values was 9.3%, indicating that the simple non-pressurized system was acceptable..

5. Discussion

5.1. Implications of Findings on System Design and Operation

Insights from dynamic modeling and analysis of solar-assisted dual-tank direct contact membrane distillation (DCMD) systems are essential for the solar thermal desalination technologies development. This system, which was developed in Israel, provides constant rates of freshwater production with fluctuating solar conditions and increases the system reliability in locations with intermittent solar resource. The two-tank system prevents any loss of temperature even during the dull-sun season, so there is always hot water on tap.

This strategy not only promotes the operational stability but also increases the thermal efficiency by rationally tuning the energy storage state by alternating the charging and discharging of tanks. This resolves challenges posed by the traditional desalination techniques fuelled by a stable heat source system, helping to reduce the energy consumption while enhancing the key performance indices, for example, gain-to-loss ratio.

The paper underlines the significance of maintaining a real-time flow rate control to overcome the effect of variation in solar intensity during the day, crucial for ensuring maximum distillate production over daily cycles. Next generation designs should be equipped with intelligent control strategies that adapt to real-time conditions on-the-fly.

It is also required to change the mindset behind historically-run single-tank



configurations, which, although may be easier and cheaper upfront, typically come with lack of performance in low solar input conditions. Yes, the switch to a dual-tank unit may include a greater initial cost of investment, but its increased value in reliability and water availability is certainly worth the extra sum.

In those areas with unreliable solar availability advanced Applications of energy storage technology leverage further and stabilize the operations. It is believed that further synergies with high-temperature concentrated solar technologies can increase capacity without great exergy destruction inherent of conventional systems.

In addition, the use of non-linear optical principles can allow even higher supersonic efficiencies in small, portable systems. "It means that by using clever ways of collecting sunlight with, for example different focusing methods, instead of just making collectors bigger, we can absorb more sunlight and keep the heat from scattering away." New advancements in the future may allow these more efficient, and flexible, technologies to bring greater efficiency and flexibility.

These results also highlight the importance of material development for solar thermal desalination and possible synergies with state-of-the-art storage technologies.[1].

5.2. Limitations of the Study and Future Directions

There are many unresolved issues in the development of solar thermal desalination technologies which would help in the successful penetration of these technologies. One of the main challenge is the variable environmental conditions in particular solar energy available which has a correlation with the efficiency and productivity of desalination plants. Differences generated by weather phenomena can cause performance variations, making it difficult to assess long-term operations of modules in different climates.

A further difficulty relates to the experimental conditions in different experiments. A significant number of studies are limited with respect to operational parameters, and test only during restricted times (e.g. 10 a.m.–4 p.m.) under favourable weather conditions. Such limited scope may lead to overoptimistic objective performance evaluations but fail in considering real-world operational conditions.

Although dynamic modeling has been developed for solar thermal desalination, their prediction for performance change with time is not so accurate. This is even more challenging when we consider heat transfer dynamics and the possibility of fouling in membrane systems, which can make long-term predictions more



difficult.

Focus on large-scale field studies that cover various climatic zones to account for how different conditions impact system operation in order to serve as a guide for the future research. Implementing such studies would enhance the relevance of the findings and guide efforts to generate more resilient systems capable of performing optimally under variable conditions.

Integration of advanced energy storage systems with solar thermal desalination systems can mitigate problems with intermittent energy source, ie solar based energy feelance with the process to be operated even during periods of low solar radiation. Investigating other arrangements, "mixed-mode" systems with the addition of photovoltaic/thermal portions and basic desalting technologies, has potential for increasing energy efficiency and robustness to changing ambient conditions.

Moreover, a combination of data-driven methods and the traditional CAD-behavioral-structural flow may improve modeling capabilities and realize optimization at system level in real time. By addressing these challenges and developing new research directions, next-generation solar thermal desalination technology could potentially solve the problem of sustainable development of freshwater.[12], [8], [1] and [4].

6. Conclusion

The study of solar driven desalination systems has offered a clear picture of how such systems perform and how sustainable and non-sustainable they are, indicating a new desperate requirement for fresh water. The results indicate that the inclusion of advanced designs, e.g., PV-T stepped solar stills yields the enhancement of thermal and electrical efficiencies. The importance of tuning system parameters such as flow rates to enhance freshwater production rate and to minimize operational cost has been emphasized in this study.

In addition, research on emerging technologies such as photo-thermal materials and nanoparticles has shown promise in breaking the energy paradigm and scaling up desalination scale while perhaps simultaneously reducing energy usage. And as these innovations develop, they pave the way for right around the corner revelations in the industry. An important feature of cockean solar stills is their flexibility to adapt to different environmental conditions such as the prevailing albedo and humidity and as such they fit well into the sustainability agenda.

But the implications of this research are also broader than the march of technology;



they suggest a new approach to how desalination can be adapted to a place. By using dynamic modeling and simulation methods, it is possible to optimize systems according to regional climate and increase performance while utilizing resources optimally.

Nevertheless, some limitations are recognized in this study. The scalability of such solutions might be limited by economic disparities between regions. Moreover, while efficiency improvements for power production are substantial, research gaps remain to comprehensively assess long term operational sustainability and environmental impacts.

It follows that future work would be better directed towards overcoming these technical challenges by investigating hybrid systems in which more than one renewable energy source is co-integrated with solar energy. Such techniques could improve efficiency and formulate holistically improved water supply options in water-stressed regions.

Continual advancement of solar thermal desalination is an encouraging path towards the sustainable water management at a global level. As the spearing of climate change and resource depletion increases, further research will be required to advance these technologies to compete with the current and future needs.

In summary, solar thermal desalination is on the verge of playing a leading role in providing sustainable solutions to the world growing crisis of water shortage. Adopting innovation with economy in mind will be key to successful deployment of such promising technologies at scale. [11] and [4].

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