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A novel hybrid compact system of photovoltaic solar still air gap membrane distillation for the simultaneous production of water and energy

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ABSTRACT

Remote arid and coastal areas have dry climates, limited freshwater supplies, and intense solar radiation. Solar still (SS) and photovoltaic (PV) technologies are preferred for small-scale water and power demands. However, these techniques have low thermal efficiency and thus limited water productivity. A compact hybrid system with a novel design combines a solar still air gap membrane distillation process with a photovoltaic panel. Outdoor experiments revealed daily average yields of produced water and power of 5.9 kg/m^2 and 0.68 kWh/m^2, respectively, when solar radiation intensity was 6.4 kWh/m^2. Throughout the day, the specific productivity (permeate flow) of potable water, electric power, and thermal efficiency coefficient is evaluated. The results indicate that as solar radiation increases, productivity increases. The daily yield of the hybrid system increased 1.6-fold when compared to a single-stage AGMD system and cascade solar still arrangement system, and 72% of solar energy was efficiently utilized.

Keywords: Solar still; Air gap membrane distillation; Photovoltaic panel; Cascade arrangement; Hybrid compact system; Hydrophobic membrane; Water desalination; Renewable energy

1. Introduction

The demand of good-quality potable water and electric energy is steadily increasing in several regions, especially in the Gulf countries. The efficient use of solar energy, which is abundant in these regions, appears to be the most attractive and suitable solution for such water and energy scarcity problem. Conventional desalination technologies, which have been widely adopted in the last few decades to ensure a continuous supply of potable water, are known to consume a huge amount of electric and thermal energy converted from fossil fuels [1,2]. Many of them require advanced infrastructure and large installations [3]. For small-scale applications, various solar desalination systems are employed with very low efficiency [4]. In fact, the low solar energy intensity results in reduced freshwater production in conventional solar distillers, with rates ranging between 0.3 and 0.7 kg/m^2·h under the standard of 1 kW/m^2 of sun illumination [5]. Solar still (SS) technology, which is the simplest solar desalination process, is a practical and easy method to provide

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drinking water from saline solutions. The technology, which is similar to the natural hydrological cycle, takes place in a "greenhouse" box and demands only solar energy [4,6–8]. The solar still device can be classified into two categories, namely passive and active, where active solar stills use photovoltaic (PV) panels, thermal collectors, and concentrators along with the distillation process and passive solar stills use solar radiation directly in the distillation unit [8–10]. The passive solar still devices have a low thermal efficiency coefficient (40%), and the permeate flux is approximately 2–4 L/m^2·d [9]. Singh et al. [4] reviewed solar distillation technology with a focus on active systems. Various designs and configurations of solar stills, including those with multistage, external condensers, a shallow water layer, and energy storage, have been described. Their review reflects the applicability of the active solar still technology despite its low productivity and efficiency. Solar photovoltaic technology and the associated market are expanding gradually. By 2015, 217.5 GW of solar PV had been installed, and that increased to 707.5 GW in 2020 [10]. However, the electric output of the panels degrades due to several environmental factors such as high temperatures and dust. This results in a low energy efficiency of PV systems: only 10%–20% of sun radiation is converted into electricity. Numerous proposals and implementations have been made to recover waste heat from these photovoltaic panels [11,12]. Kumar and Tiwari [12,13] examined the possibility of reusing the heat generated by the photovoltaic panels to generate fresh water via solar stills. Saeedi et al. [13,14] acquired additional results from an optimization study on the performance of a comparable PV/T (photovoltaic/thermal) solar still system. The mass flow rate and the number of PV/T collectors were shown to have a significant effect on the integrated solar power desalination system's energy efficiency. An experimental double basin solar still with evacuated tubes was constructed using locally available materials to perform research on solid fins. Compared to a two-basin solar still with evacuated tubes, fins enhance distillate yield 25%. It also boosts distillate output in sunny and off-sunny conditions [15]. Another experimental investigation was undertaken to investigate the influence of vertical and inclined fins on the performance of solar stills. Solar stills with fins (vertical and inclined) produce a higher yield (26.77% and 24.19%, respectively) than conventional solar stills [16]. Hitesh Panchal et al. investigated the distillate yield of stepped solar stills (SSS) utilizing varied concentrations of MgO and TiO_2 nanofluids. The results indicate that increasing the nanofluid concentration increases the production of (SSS) distillate (51.7% and 61.89% for MgO and 33.18% and 41.05% for TiO_2, respectively) [17].

Membrane distillation (MD), a new technology that combines heat and the mass transfer process, has recently been introduced [18,19]. Membrane distillation (MD) relies on a partial vapor pressure difference across the membrane, which is usually created by a temperature difference [20,21]. Despite the fact that MD was proposed decades ago, it is still in the early stages of commercial development [22,23]. The low recovery rate, extreme temperature polarization, and, to a lesser extent, fouling of the membrane, especially when treating concentrated feed solutions, are all key reasons for its late commercialization [18]. In the MD process, microporous hydrophobic membranes such as polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE), and polypropylene (PP) are frequently investigated [18,24]. The hydrophobic membrane allows water vapor to pass through it while preventing liquids, where some liquids flow and spread over the membrane surfaces to form a film, whereas others wet them only slightly, resulting in drops at a specific contact angle [18,25,26]. The MD process can be classified into four different configurations, as illustrated in Fig. 1, including (a) direct contact membrane distillation (DCMD), in which the membrane is in direct contact at both sides of the membrane; (b) air gap membrane distillation (AGMD), in which an air gap between the membrane and the condensation surface is introduced; (c) sweeping gas membrane distillation (SGMD), in which an inert gas is placed to sweep the membrane; and (d) vacuum membrane distillation (VMD), where the vacuum is applied to the permeate side by means of a vacuum pump for condensing the vapor. The MD configurations differences depend on how the vapor is condensed or removed from the membrane module, and the advantages, and disadvantages of all four configurations depend on the type of application for treating the feed solution [27–29]. The AGMD process has many appealing characteristics when compared to other MD configurations, with one of the most significant advantages being the ability to recover the latent heat of vaporization and a much higher thermal efficiency than other DCMD configurations [18].

Membrane distillation (MD), which is a rapidly increasing hybrid thermal-membrane technology, has a major advantage: the ability to be powered by low grade heat such as solar thermal energy and waste heat [18,30–32]. Therefore, an increasing number of studies have addressed the MD integration with thermal desalination, including solar stills [5,33]. One of the early studies on coupling solar stills with membrane distillation (MD), conducted by Banat et al. [34], aimed to improve the limited production rates of a standalone MD and single still systems. Single solar stills were used for brine heating and freshwater production. Results based on indoor and outdoor experiments have shown that the MD-produced water flux is much higher than that of solar still; an increase of about 20% of production by the hybrid system compared to a single MD module was obtained. Hizam et al. [35] proposed a new concept of salt harvesting and water production using a coupled solar still and MD. Basic solar still experiments have been conducted to provide insights into better MD–solar still integration. Signorato et al. [36] applied the first and second laws of thermodynamics to a passive multistage MD device operating by solar energy with no moving parts. The authors compared the second law efficiency of the proposed configuration to other desalination processes. They observed that the proposed passive solar MD has a much higher second law efficiency than passive solar stills but lower than that of active direct contact membrane distillation (DCMD). New innovative cogeneration systems for simultaneous power and water production have been proposed recently. Wang et al. [5] designed and constructed a PV-MD device that can ensure continuous and stable freshwater production rate higher than 1.64 kg/m^2·h from red seawater and producing electricity with an efficiency higher than 11%. In this design, the PV panel is used to generate electricity but also used as a photothermal component for heating water. Recently, new innovative

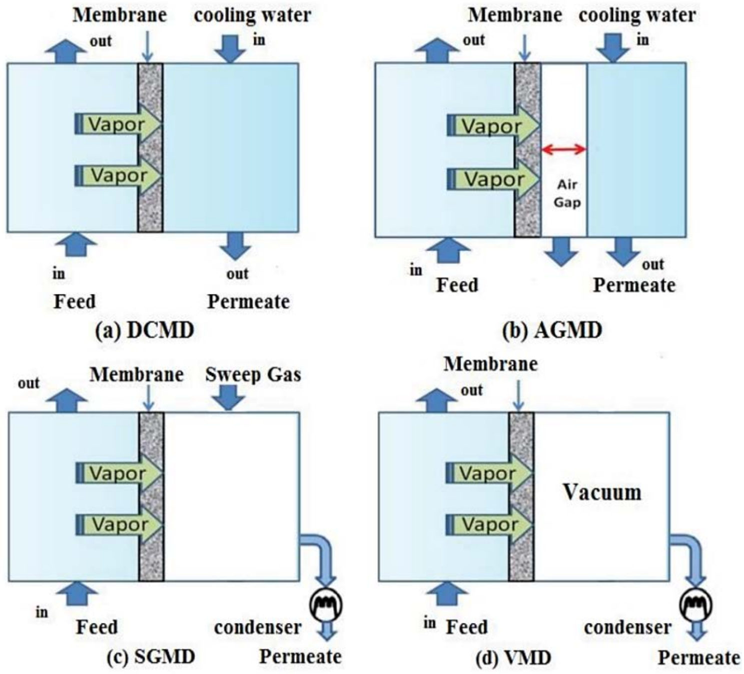


Fig. 1. MD configurations [24].

cogeneration systems for the simultaneous production of electricity and water have been proposed. Wang et al. [5] designed and constructed a photovoltaic membrane distillation (PV-MD) apparatus capable of producing freshwater at a rate more than 1.64 kg/m^2·h from red seawater and producing energy at a rate greater than 11%. The photovoltaic panel is employed not only to generate electricity, but also as a photothermal component for heating water in this design. Huang et al. [37] focused on solar-driven evaporation in order to design and construct a hybrid cogeneration system consisting of a backside photovoltaic panel and a multistage membrane distillation (PV-MMD). To maximize the conversion of solar energy to electricity, an evaporative cooling process is used, which results in a significant decrease in the operating temperature. Additionally, the PV cells' dissipated heat is used as a source of heat for the feed of the MD process. A theoretical model was developed and validated using experimental data to examine the overall performance of a coupled power and water purification system.

The present work describes a novel cogeneration power and water system that consists of a photovoltaic solar still air gap membrane distillation system (PV-SS-AGMD). The proposed system is designed similarly to a conventional flat plate heat exchanger, but is more compact, adaptable, and simple. The energy input is minimized by recovering the rejected heat from the PV panels and reusing it to drive the MD system. The sections that follow describe the proposed system in detail, as well as the experimental approach and a discussion of the obtained results.

2. Description of the proposed system

A portable hybrid photovoltaic solar still and air gap membrane distillation (PV-SS-AMD) system has been developed, which utilizes solar energy to generate electricity and water simultaneously. Its primary objective is to recover the vast majority of the solar radiation incident (about 85%) on the photovoltaic panel and use it as a source of heat for evaporation, then namely, to generate freshwater via solar still membrane and distillation processes.

The proposed module is designed and constructed similarly to a flat plate heat exchanger. The photovoltaic panel, membrane distillation process, and solar still are all built and integrated in such a way that they are simple to run and maintain. For their compact ability and thermal efficiency, a cascade-type solar still and an MD module with an air gap design were chosen. Thus, the module should deliver power from photovoltaic cells and fresh water from the MD and solar still conveniently, reliably, and efficiently. The battery bank, photovoltaic cells, feed, distillate, and rejected brine streams are all positioned to minimize clutter and disorder. Fig. 2 shows the hybrid system's inputs and outputs. The solar still's cover glass absorbs transmits the incoming sun radiation. In the PV panel, some of this solar energy is transformed to electricity and heat. This latter is the major source of energy for the AGMD unit beneath the panel. This latter is the major source of energy for the membrane distillation and solar still processes. The MD feed water is heated by a back layer (Tedlar) in the PV cells. The PV panel's solar cells capture solar heat, which is then transported to the two desalination systems. To maximize absorption effectiveness, the gadget is angled at the same latitude as the location. The slope angle determines the height of the solar still obstacles and the distance between the light transparent cover glass and the PV panel surface. The slope must also be sufficient to allow simple clearance of condensate produced on the cover glass' inner surface. The microporous and hydrophobic membrane directs unrestricted evaporation down the pores. The condensing layer serves as a condensing surface for water vapor traveling between the air gap and the saline solution meniscus at the membrane pore entrance. In between the support nettings, the membrane ensures the correct volume of salt water and an adequate air gap (through aluminum sheet and glass). The condensed water vapor is removed by a distillated water tube, while the brine produced by the solar still and MD systems is removed by gravity using brine tubes at the structure's base. The solar still and MD systems' stepwise cascaded obstacles and nettings contribute to increased freshwater output. It's worth noting that both desalination systems' condensation was caused by contact with ambient air. Unlike most traditional MD systems, no additional cold water-cooling structure is required. Thus, the suggested method is a two-stage distillation system that maximizes the use of available thermal energy. The technical specifications of the hybrid system are presented in Table 1, while the main characteristics of the PV collector are given in Table 2.

3. Experimental set-up

The Experiments were conducted outdoors in order to prove the feasibility of simultaneously producing electricity and freshwater. Fig. 3a depicts the completed hybrid system in its entirety, whereas Fig. 3b depicts it from the top, showing the condensation occurring on the cover of the solar still. The apparatus's geometrical design and specifications are detailed in Fig. 4. The constructed system is shown to be 30 cm wide by 53 cm long, with an active area of 20 cm × 43 cm. The cascade's steps are 40 mm high. Additionally, the transparent glass, photovoltaic panel, heat absorber, membrane, and condensation sheet all have the same dimensions to simplify comparison and calculation.

The experimental observations and measurements of the hybrid system were made at latitude 40°11′00″ N and longitude 44°31′00″ E that is 1,000 m above sea level. The devices were oriented with their absorbing surfaces facing south. The main experiments were conducted from 9:00 am to 7:00 pm during a typical summer day, when the ambient temperature fluctuates between 25°C and 35°C. The initially prepared model aqueous NaCl solution with a salt concentration of 20 g/L was heated up to 50°C and then fed into the device. The volume of solution feeding the solar still part was 1.4 L, and it was in direct contact with the PV panel-absorber. The

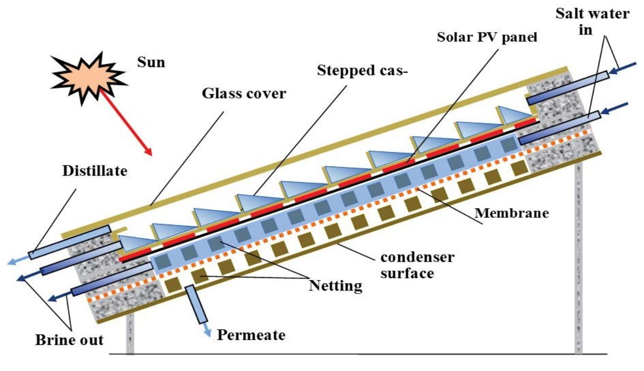


Fig. 2. Schematic representation of the integrated PV solar still air gap membrane distillation (PV-SS-AGMD) system.

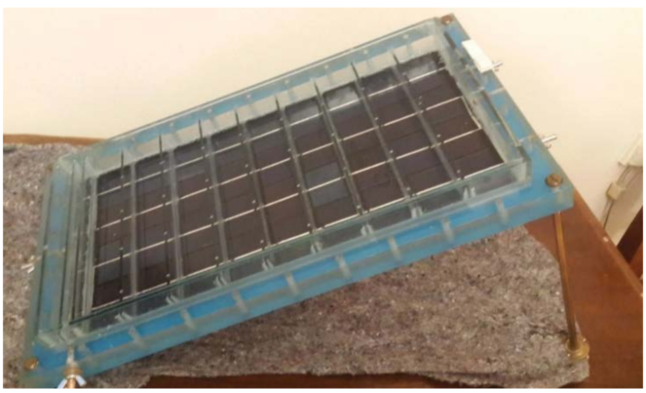
Table 1
Technical specifications of the hybrid system

Technical Specifications	Length (cm)	Width (cm)	Thickness (cm)
Hybrid system	53	30	6.5
Hardened cover glass	48	25	0.4
PV panel absorber	43	23	0.55
Solar cell (36)	5.3	3.8	0.025
Condensing sheet	53	30	0.2
Membrane	53	27	0.016
Glass fins (7)	22	4	0.3

Table 2
Characteristics of the PV panel

Characteristics	Symbol	Unit	Value
Maximum power	P_m	W	108,502
Optimum operating voltage	V_m	V	17.937
Optimum operating current	I_m	A	0.6049
Open circuit voltage	V_{oc}	V	22.6
Short circuit current	I_{sc}	A	0.649

(a)



(b)

Fig. 3. (a) General view and (b) top view of the hybrid system.

PV panel was heated as a result of absorbing solar electrical–magnetic electromagnetic rays. The MD feed water, which has a volume of 0.9 L, was heated (average temperature 50°C) by the contact with the back layer (Tedlar) situated in the back part of the PV panel. Concentrated solutions, via a desalination process, were removed from the MD and solar still parts by the brine tubes serving as a concentrated solution outlet. The distillate formed on the surface of the glass flowed down and gathered in the U collector. The 6° inclination angle of the glass promoted the fast removal of pure water by the distillate tube and prevented the phenomenon of re-evaporation (double distillation). A similar distillation process was also performed at the MD part, in which, passing through the membrane, water vapor molecules condensed on the aluminum layer and were removed from the device. The amount of collected distilled water was measured at hourly intervals. Corresponding to the amount of distillated water removed, new feed portions were added. Therefore, additional feed was continuously dosed into the system.

Concerning the electrical measurements related to the PV panel, the following test procedure was followed:

- Connect the variable resistance circuit to the unit of the PV panel.
- Connect the ammeter to the variable resistance, and the unit of the PV panel in series.
- Connect the voltmeter to the variable resistance, and the unit of the PV panel in parallel.

Determine the short circuit current of the PV panel (maximum current, minimum resistance, and voltage) and an open circuit voltage (minimum current, maximum resistance, and voltage). To conduct an appropriate investigation of the integrated solar photovoltaic and desalination system's performance, it is necessary to compare its behavior to that of standalone systems. As a result, three experimental setups were constructed and evaluated concurrently under identical operating and meteorological conditions. The first and second arrangements correspond to the AGMD unit (Fig. 5a) and solar still (Fig. 5b), respectively, while Fig. 2 depicts the third setup (hybrid system). Our main purpose in this work was to analyze the overall performance of each of the systems, particularly the hybrid one, in terms of freshwater productivity, thermal efficiency, and electrical power generated. Therefore, the following quantities were evaluated for several cases: The specific freshwater productivity, expressed in kg/m²·d, is the permeate flux obtained by membrane distillation MD (J_{MD}), the solar still (SS) (J_{SS}), and the hybrid system (J_H), respectively.

The electrical energy produced in a day by the PV panel (P_H), expressed in W/m²·d. The thermal efficiency of the MD and the SS system is given, respectively, by:

$$\eta_{MD} = \frac{h_{fg} J_{MD}}{Q_R} \tag{1}$$

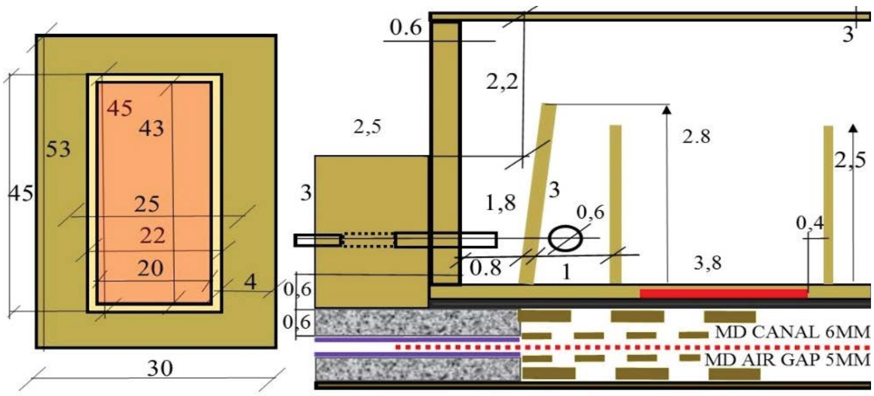


Fig. 4. Geometric specifications of the proposed apparatus.

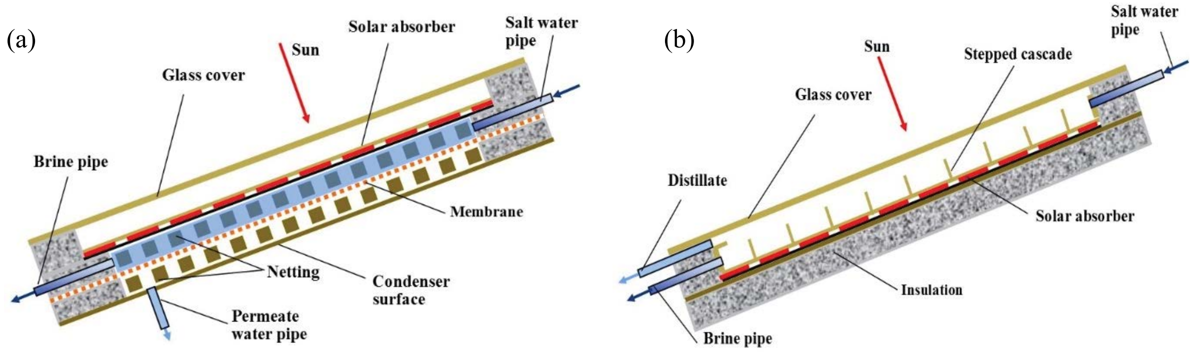


Fig. 5. Diagrams of (a) the one-stage AGMD process and (b) the solar still process.

$$\eta_{SS} = \frac{h_{fg} J_{SS}}{Q_R} \quad (2)$$

where Q_R is the amount of solar radiation during a day, given in kWh/m²·d, and h_{fg} refers to the latent heat of evaporation, which is equal to 0.662 kWh/kg for an average temperature of 50°C.

4. Results and discussion

Over the course of 3 d, a series of experiments were carried out to evaluate the performance of the proposed stand-alone and hybrid systems in comparison to one another. Various measurements of the process variables, such as solar radiation intensity, ambient temperature, humidity, and permeate flux and brine flow rates, have been performed out in the laboratory setting.

Fig. 6 depicts the specific productivities (permeate fluxes) produced by the three systems at the ambient temperatures at different times of day. The experiments were conducted during a typical sunny day, when the maximum air temperature was 31°C and the solar radiation was 6.22 kW/m². The intensity of radiation varied during a day from 640 to 990 W/m², while the dynamics of variation during solar and cloudy days matched the temperature changes. The wind velocity did not exceed 3 m/s during a day. The experiments started at 9 a.m. and ended at 7 p.m. The startup time of the device was 20–30 min. The first results were recorded when the temperature of water increased by 10°–15°. The maximum value of the rise was reached at 3 to 4 p.m. The temperature of the solution rose rapidly in the case of one-stage MD and SS devices, but their amount was less than in the two-stage hybrid PV-SS-AGMD system. The temperature and, consequently, the partial pressure, had the main influence on the output. As this dependency was exponential, temperature rises at high values resulted in a significant increase of the specific productivity. At the end of the experiments, the 7 p.m. summary of hourly outputs performance of the three processes was as follows:

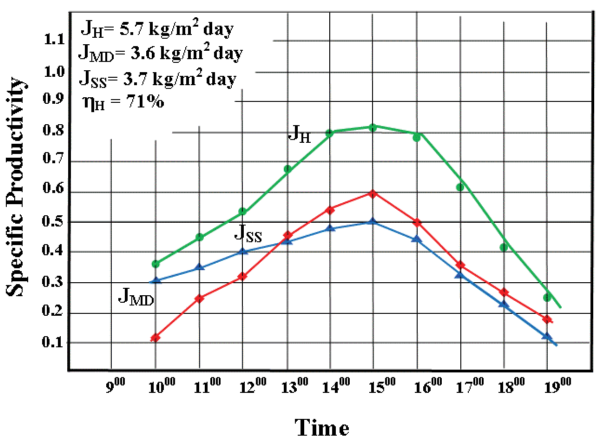


Fig. 6. Specific productivity at temperature difference across membrane (a) and different times of day (b): J_H—photovoltaic hybrid desalination device; J_{MD}—MD device; J_{SS}—Solar still; T_H—ambient temperature. The solar radiation is 6.22 kWh/m²·d.

- AGMD process—J_{MD} = 3.6 kg/m²·d, η_{MD} = 38% P_{MD} = 0 (Fig. 5a).
- SS process—J_{SS} = 3.7 kg/m²·d, η_{SS} = 39% P_{SS} = 0 (Fig. 5b).
- PV-SS-AGMD system J_H = 5.7 kg/m²·d, η_H = 71% P_H = 0.640 kWh/m²·d (Fig. 2).

The permeate fluxes of the hybrid system increased to 55%. The amount of electrical current produced by PV panels of the hybrid device was 0.640 kWh/m²·d, which was determined by the sum of products, and resulted from multiplying the voltmeter by the ammeter recorded data (P_H = ΣUiIi). Experimental investigations were carried out to investigate the power produced by PV panels integrated in a hybrid system and to evaluate the fluxes and the quality of drinking water produced by the hybrid system. The experiments were conducted again when the radiation intensity was 6.1 kWh/m²·d, and the maximum productivity was recorded at temperature difference across membrane (ΔT) 25°C and 15:00 o'clock as shown in Fig. 7a and b.

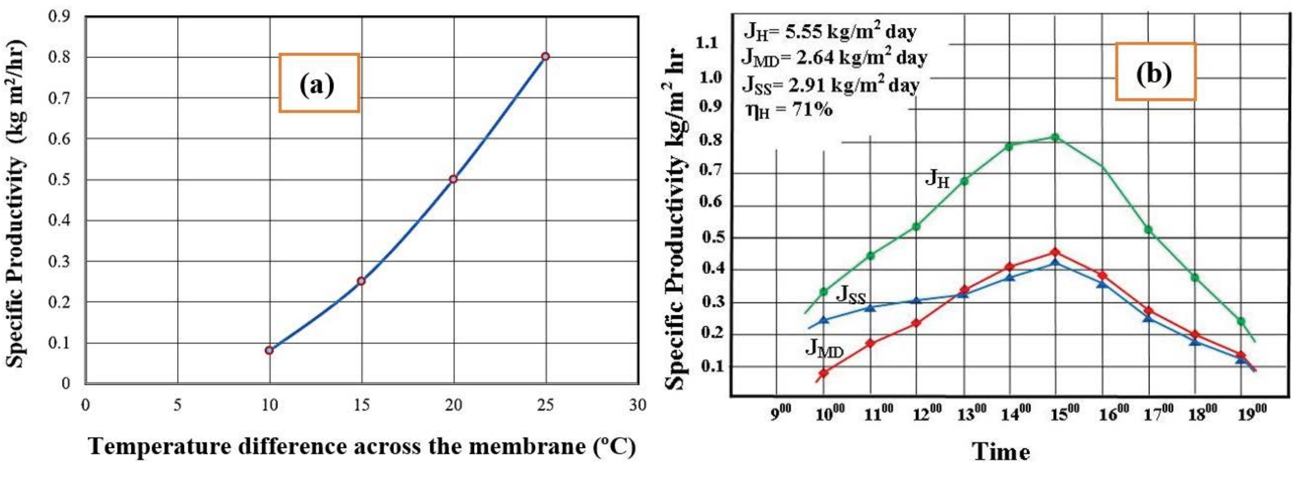


Fig. 7. Specific productivity at temperature difference across membrane (a) and different times of day (b): J_H—photovoltaic hybrid desalination device; J_{MD}—MD device; J_{SS}—solar still; T_H—ambient temperature. The solar radiation is 6.1 kWh/m²·d.

Before absorption by PV panels, solar rays passed through two saline solutions, which were is on the light side of the panel. The first portions of condensed water vapor at the SS side flowed onto the glass surface and were collected in the collector. Although, at 10 a.m., the amount of permeate on the MD side was very small, at 1 p.m. the amounts of water produced from the two sides became equal. Up to the end of the experiment, the amount of permeate at the membrane side remained large. The solar radiation intensity reached its peak value of 1,010 W/m^2 at 1 p.m., while the specific productivity reached its maximum value of 0.81 kg/m^2·h at 3 p.m. In 3 h, it achieved almost 50% (5.55 kg/m^2·d) of daily specific productivity, because the temperature of the saline solution had its maximum value after noon. The variation dynamics of drinking water output produced by the hybrid device, compared with the variation of electrical energy produced by the PV panel during a day, are presented in Fig. 8. The maximum value of productivity, at 3 p.m., fell short of the maximum value of electrical power. When the sun was at its zenith and electromagnetic rays fell on the perpendicular absorber surface, the power was the largest, 108 W/m^2. The temperature of saline water at that point was still low because of the thermal inertness of the hybrid device. Under the influence of ambient factors, the amount of product was 5.9 kg/m^2·d and 680 Wh/m^2·d.

The specific productivity of solar desalination plants is defined by Eq. (3):

$$J = \phi \frac{Q}{580} \quad (3)$$

where J – specific productivity, kg/m^2·d, φ – coefficient of solar heat consumption, Q – intensity of sun on 1 m^2 horizontal surface (kcal/m^2·d), amount of heat required to evaporate 1 kg water = 580 kcal/kg.

Heat losses in desalination plants of total solar heat are allocated to (i) saline water's surface and bottom reflect sunlight, (ii) glass surface reflection, (iii) ray reflection and condensate heat absorption, (iv) heat convective flow losses, and (v) secondary condensate evaporation and other loses.

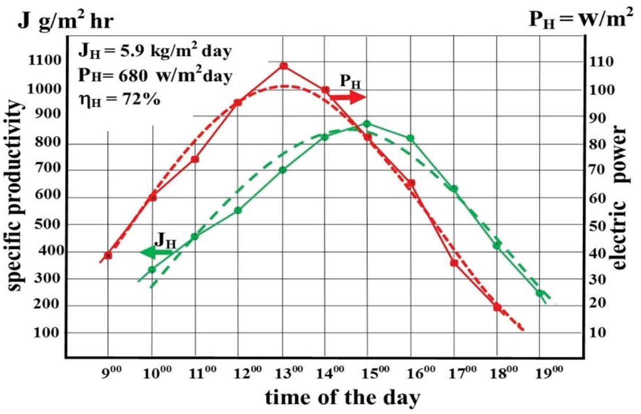


Fig. 8. Specific productivity (J_H) and electric power (P_H) photovoltaic hybrid desalination device at different times of day. The solar radiation is 6.4 kWh/m^2·d.

The ratio between the operating electrical power (P_{PV}) and the solar irradiation (Q_S) energy received on the total surface (F_{PV}) of the PV array can be used to calculate the efficiency of electrical power operation subsystems (PV) as given in Eq. (4) [38].

$$\eta_{PV} = \eta_{max}\eta_l = \frac{P_{PV}}{\eta_b F_{PV} Q_S \tau} \quad (4)$$

where b is battery efficiency, F_{PV} is the surface area of PV modules, Q_S is the average daily solar irradiation, τ is the average number of sunny hours, η_l is connection losses, and η_{max} max is the maximum power point efficiency of PV modules.

During tests, the concentration of dissolved salts in permeate and distilled water did not exceed 15 mg/L. The selectivity or percentage rejection of the hybrid process was determined by Eq. (5).

$$K = \left(1 - \frac{C_1}{C_2}\right) \times 100\% \quad (5)$$

At 7 p.m., the percentage rejection was 99.99%, indicating the high quality of the produced water. Breaks during the night had no effect on the membrane. After 300 h of operation, the percentage rejection and output of the photovoltaic hybrid system remained constant. It is possible that, during this interval, variations in the solution temperature in the 20°C–60°C range had little effect.

The results presented in this study have focused on the most important performance parameters of the integrated electricity and water production. Other details, such as the temperature variation with time at different locations of the system, are of importance to conduct a more refined theoretical and experimental study. They can be considered in future work. Nevertheless, the present results give a clear indication of the potential of the proposed system. Further studies will be very important for process optimization.

5. Conclusion

This work outlines the design and construction of a novel PV-SS-AGMD hybrid system developed to meet the needs of smaller communities and families. We present the results of its performance under outdoor conditions. The integrated photovoltaic panel desalination device is a means of getting electricity and generating thermal energy for water production. The device includes air gap membrane distillation (AGMD) and solar still (SS) units that are separated by a PV panel. Experiments with them operating side by side in field conditions showed that the water specific productivity of the hybrid system increased by about 55% in comparison with a MD unit or SS unit alone. The variation in water productivity and electrical energy during a day was investigated, showing their significant dependence to the solar radiation intensity. The cumulative values of water and electrical energy generated by the PV panel obtained when using the solar hybrid MD-SS PV-SS-AGMD system reached 5.9 kg/m^2 and 680 Wh/m^2 during a day, respectively, when the solar radiation was 6.4 kWh/m^2·d. The coefficient of the solar energy utilization of the proposed system was more than 72% for all experiments. The percentage rejection was 99.99% for an aqueous NaCl solution with a salt concentration of 20 g/L, which indicated the high quality of the water produced. Experiments conducted in outdoor conditions demonstrated the benefits of an integrated compact system capable of producing electricity and freshwater simultaneously, as well as favorable prospects for further improvement and optimization.

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