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Performance and cost evaluation of an autonomous solar vacuum membrane distillation desalination plant

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ABSTRACT

The aim of this work is to investigate the overall performance of an autonomous solar vacuum membrane distillation (VMD) plant for seawater desalination. The system performance was evaluated in terms of several indicators, such as membrane flux rate (MFR), gained output ratio (GOR), performance ratio (PR), recovery ratio (RR) and specific thermal energy consumption (STEC). The obtained results were compared with the reported values from published operational parameters of various solar-powered membrane distillation systems previously tested in literature. The maximum values of MFR, GOR, PR and RR were found to be 14 L/h·m^2, 3.3, 0.95 kg/MJ and 4.66%, respectively. In addition, the minimum value achieved for STEC was 290 kWh/m^3 by a recovery of the latent heat of condensation. Besides, a sensitivity analysis was carried out to study the effect of some operating parameters on GOR performance. The results showed that the GOR can be maximized at low feed flow rate and high feed temperature. A higher GOR value can also be attained with an increase in vacuum level and solar collector area. Finally, an economic study was performed to estimate the expected cost of distilled water produced by the solar VMD plant.

Keywords: Seawater desalination; Vacuum membrane distillation; Solar energy; Performance evaluation; Sensitivity analysis; Economic study

1. Introduction

Membrane distillation (MD) is an emerging, thermally driven membrane technology used for desalination of seawater or brackish water, solution concentration, recovery of volatile compounds from aqueous solutions and other separation and purification processes. The driving force for mass transfer is the vapor pressure gradient between the hot feed side and the distillate side of a hydrophobic micro-porous membrane [1,2].

The advantages of MD compared to other desalination technologies are as follows [3]: (i) low operating temperature and lower vapor space required than traditional distillation, such as multi-stage flash (MSF) and multiple effect distillation (MED); (ii) lower operating pressure when compared with conventional pressure-driven membrane processes, such as reverse osmosis (RO); (iii) nearly a complete salt rejection; and (iv) the performance is not limited by high osmotic pressure or concentration polarization.

Four major MD configurations have been identified: Direct Contact (DCMD), Air Gap (AGMD), Vacuum membrane (VMD) and Sweep Gas (SGMD). The DCMD, AGMD and VMD are most commonly suited for desalination applications [4]. DCMD involves a cooled liquid is in direct contact with the membrane at the permeate side. The evaporation takes place at the feed-membrane surface. The vapor is moved by the pressure difference across the membrane

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to the permeate side and condenses inside the membrane module [5]. DCMD is the simplest MD configuration. However, the heat losses by conduction through the membrane is higher than other configurations due to the existence of a continuous contact between the membrane surfaces and the feed (hot) and permeate (cold) solution.

The second configuration, AGMD has an additional air gap interposed between the membrane and the condensation surface leading to an increase of the mass transfer resistance. The vapor crosses the air gap to condense over the cold surface inside the membrane module. The benefit of this design is the reduced heat lost by conduction [6]. However, additional resistance to mass transfer is created due to the air gap, which limits the permeate flux.

VMD process is similar to AGMD, but the permeate side is maintained at pressure lower than the equilibrium vapor pressure. By applying a continuous vacuum in the permeate side, the vapor pressure difference across the membrane is greater, and hence higher permeate flux can be achieved. An experimental study carried out by Ku and Lee [7] to compare the efficiency of DCMD, AGMD and VMD using a salt solution feed showed that VMD presented the highest flux among the three MD configurations. The vacuum also reduces the formation of boundary layer on the permeate side, resulting in a decrease in the conductive heat loss across the membrane and improvement of the VMD performance [8]. However, the disadvantage of VMD lies in the fact that it typically requires an external condenser and vacuum pump to facilitate the transfer of the permeate water vapor across the membrane, causing extra energy consumption.

One of the possible solutions to improve energy efficiency in MD is the coupling of this technology with solar energy since MD requires relatively low temperatures to generate the thermal driving force across the membrane (typically within the range of 60˚C–80˚C), a temperature level where solar thermal flat plate collectors perform economically and well [9–12]. Two different configurations were developed: compact system, where the MD feed solution is directly heated by passing through the solar thermal collector, and two-loop system, where the feed solution is heated indirectly in a heat exchanger by the hot fluid from the solar thermal collector [12].

Solar-powered membrane distillation (SP-MD) desalination systems have been proposed as promising technology in remotes rural areas with strong solar radiation to provide people with clean potable water [9,13]. However, despite the various SP-MD pilot systems constructed and tested over the two past decades, such systems have not been commercialized or implemented on a large scale yet, mainly because it has been found to be less economical and energy efficient than other, more mature desalination technologies such as solar photovoltaic reverse osmosis (PV-RO) and solar distillation. Nevertheless, SP-MD systems are getting much more attention, as a result of the growing interest in renewable energy-driven desalination [13,14].

A number of projects that focus on incorporating solar energy with MD technology have been reported in literature. In 1991 a SP-MD simulation was demonstrated by Hogan el al [15] at the University of New South Wales in Australia. The simulation considered a system consisting of hollow-fiber MD membranes and 3 m^2 flat plate solar collectors. The results show that system would produce 0.05 m^3/d, given the small distillate flux the plant was proposed for domestic applications.

Another SP-MD unit was constructed in 1994 by Bier et al. [16] using an AGMD module instead of the DCMD module tested in the SP-MD pilot plant constructed by Hogan et al. The latent heat recovery process in this late pilot plant was integrated with MD in a spiral-wound membrane module. However, the additional mass transfer resistance created by the air gap resulted in a large reduction in the trans membrane water flux.

Koschilkowski et al. [9] used a similar membrane module as that used by Bier et al. in their study of a SP-MD pilot plant. According to their calculations, without heat storage, the plant can distill 150 L/d of water in the summer in a southern country.

Banat et al. [17] integrated a MD module with a solar still to produce potable water from simulated seawater. In their investigations the solar still was used for both seawater heating and potable water production. The effect of some factors affecting flux of the membrane module was also investigated. Their experimental studies showed that the contribution of the solar still in the distillate production was no more than 20% of the total flux.

Ding et al. [18] developed a dynamic mathematical model to simulate the performance of a SP-MD pilot plant. The system was tested at Fraunhofer ISE in Freiburg. A PV power supply was not integrated, all electrical components were connected to the grid. When investigating the dynamic behaviour of the system, it was found that the distillate flux followed very closely the changes in the hot inlet temperature of the module. The results show that the maximum distillate output was 15 L/h, and the total distillate produced was 130 L/d.

Banat et al. [19,20] reported on results from two solar driven AGMD plants. One is a compact unit installed in the northern part of Jordan (Irbid) and has been operated with brackish water since September 2005 and the other is a large unit installed in the southern part of Jordan (Aqaba port) and has been operated with untreated seawater since February 2006. The compact system uses spiral-wound membranes with an effective area of 10 m^2. The water was heated by passing through a corrosion resistant flat plate collector, with an area of 5.73 m^2. A PV module was used to provide electrical power to a direct current (DC) pump and magnetic valves. The system produced a maximum distillate output of 120 L/d.

The large system had two distinct loops. The solar loop consisted of 72 m^2 flat plate collector and a 3 m^3 storage tank which is used to collect surplus heat throughout the day and extend operation into the evening. The inlet temperature of the system was maintained at 80°C and excess heat was diverted to the thermal storage tank. The desalination loop contained 4 MD modules, each with an effective membrane area of 10 m^2. The maximum distillate flux of 1.5 L/m^2 h was reported. The use of thermal storage enabled he system to operate for a further 6 h after sunset, giving a maximum daily output of 792 L/d.

Koschikowski et al. [10] installed and tested six compact solar driven MD units in various locations. The first of these systems was placed in PozoIzquierdo (Gran Canaria) in December of 2004, followed by systems in Alexandria

(Egypt), Irbid (Jordan), Kelaa de Sraghna (Morocco), and Freiburg (Germany). The final system was installed in Tenerife (Spain), in December 2007. These systems were designed to produce 60–150 L/d of fresh water.

Between 2010 and 2011, other three compact systems have been installed in Tunisia and Tenerife and two more two loops systems have been installed in Gran Canaria and Pantelleria (Italy), this latter being powered by a hybrid system using solar energy and waste heat from diesel engines, with a nominal production up to 5 m^3/d [21]. Another two-loop system was installed in the north of Namibia in 2010 [22]. This system, with a total membrane area of 168 m^2 and 232 m^2 of flat plate solar collectors, was designed for the fresh water production of up to 4 m^3 in 24 h operation from a brackish water well.

From 2012 to this day, different autonomous SP-MD systems, covering a wide range of capacity, have been developed, installed and monitored. A comprehensive review can be found in the recent literature [23].

In this paper, the techno-economic performance of a solar-powered VMD system is investigated. The pilot plant was installed in Tunisia in a plat-form in the village of orphaned children (S.O.S MAHRES). This is a non-governmental social and foster care of children without family support [24]. The installation is completely autonomous using only solar energy for its operation. The electrical energy required to operate the system is generated by means of a PV cells field, and heating the seawater is provided by a solar collector field.

2. Pilot design

The choice of pilot design and dimensions of its components is the result of work carried out in the European project MEDINA (Membrane-Based Desalination: An Integrated Approach) [25]. Since the implementation of the pilot plant in 2011, the whole installation functioned satisfactory from technical point of view and the quality of the water produced is very convenient to use. The schematic diagram of desalination plant is shown in Fig.1.

The main components of the solar VMD plant are [11,26]:

- A capillary microfiltration module, provided by PALL Company, consisting of 806 fibers (PVDF) with an internal diameter of 1.4 mm. This module has a length of 1.129 m and offering a total membrane area of 4 m^2. The characteristics of the membrane module are given in Table 1 [26].
- A field of solar collectors with a total area of 70 m^2 comprising 7 lines of 5 collectors in series.

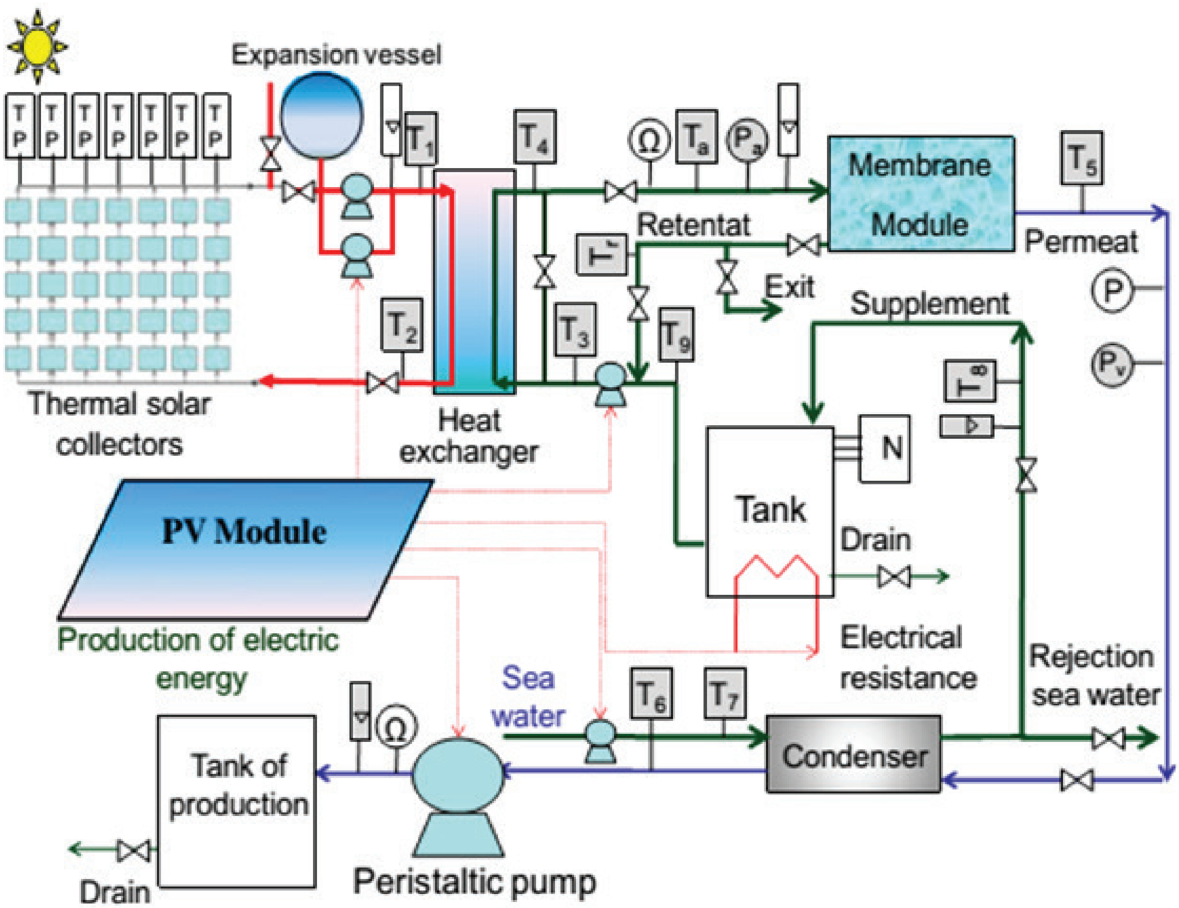


Fig. 1. Design of the solar vacuum membrane distillation (VMD) desalination plant [11].

Table 1
The membrane module characteristics [26]

Commercial reference	UMP 3247 R
Material	PVDF
Number of fibers	806
Inner diameter (mm)	1.4
Outer diameter (mm)	2.2
Thickness of the membrane (mm)	0.4
Module length (m)	1.129
Nominal pore size (μm)	0.2
Porosity (%)	75
Area (m^2)	4
Permeability at 20 °C (s $mol^{1/2}$ $kg^{-1/2}$ m^{-1})	1.92×10^{-6}
Tortuosity	2.1

- A system of PV solar cells composed of modules with a peak power of 2.1 kW.
- Feed pump ensuring the supply of seawater (flow up to 2500 L/h, power: 1 kW).
- Circulator pump for circulating the coolant fluid in the collector field (power: 0.5 kW).
- Peristaltic pump that can provide vacuum and extract the flow of distillate (power: 0.5 kW).
- Plate heat exchanger with 27 titanium plates of 26 kW power and offering an exchange area of 1.08 m^2.
- Tubular condenser in titanium 60 kW power with 41 tubes, 7 mm internal diameter and 1 mm thickness. The condenser was designed to ensure the condensation of vapor from the membrane module at 70°C.
- Instrumentation of process control and regulation.
- A 1 m^3 tank for fresh water production.
- A mixing tank (volume: 80 L) which mixes the concentrate exiting from the membrane module and the supplement out of seawater.
- An electrical resistance immersed in the mixing tank which allows heating its contents when the electric charge accumulated in the batteries exceeds the power necessary to operate the pumps.

The coolant exiting from the solar collector field is directed to heat exchanger to provide heat to the seawater at the inlet of membrane module. The concentrate flow leaving the membrane module is then fed to the heat exchanger and is mixed with an auxiliary of preheated seawater. The produced vapor is condensed into freshwater on a tubular exchanger. After condensation, a peristaltic pump mounted downstream of the condenser ensures circulation of the desalinated water to reservoir production. The latent heat recovered from condensing steam is used to preheat the auxiliary seawater [26].

Table 2 summarizes the operational parameters of the solar VMD plant with some established SP-MD systems constructed and tested in the past decades. It can be seen from this table that most of the pilot plants operated in areas with high solar radiation, and used common flat plat collectors, since SP-MD systems required feed temperatures between 60 and 80°C, as mentioned earlier. It can also be seen that AGMD is the most frequently used SP-MD configuration because of its high energy efficiency and capability for latent heat recovery [27]. Despite the many benefits of VMD process, very few experimental studies that estimate the potential of this technology coupled with solar energy have been reported so far, mainly because of the complicated set-up procedure for VMD that comes from the need of a separate vacuum pump and a condenser.

3. Performance indicators

The MD systems are commonly evaluated using several performance indexes, including membrane flux rate (MFR) achieved, specific thermal energy consumption (STEC), gained output ratio (GOR), performance ratio (PR), recovery ratio (RR) and the energy recovery scheme applied.

3.1. Membrane flux rate (MFR)

The performance of SP-MD systems is sometimes stated in terms of number of liters that may be purified per day. Since each MD system has different configuration and different size, it is more convenient to make comparison with water production per unit area of membrane surface, measured as kg/m²·h and reported as LMH (L/m²·h). The MFR is mathematically calculated as:

$$MFR = \frac{\dot{m}_d}{A_m} \quad (1)$$

where $\dot{m}_d$ is the distillate mass flow rate (kg/h), and A_m is the effective membrane area (m^2).

3.2. Specific thermal energy consumption (STEC)

Another interesting characteristic parameter for a desalination system is the STEC defined as the energy input required to produce 1 m^3 of distillate (i.e., ratio of energy supplied to the volume of produced fresh water). The lower is the value of the STEC the more economical is the MD process.

$$STEC = \frac{\rho . Q_h}{\dot{m}_d} \quad (2)$$

where ρ is the density of water (kg/m^3) and Q_h is the external thermal energy input (kW). Q_h can be calculated using the following equation:

$$Q_h = \dot{m}_f . C_p . \left(T_{f,i} - T_{fo}\right) \quad (3)$$

where C_p is the specific heat capacity of feed water (kJ/kg·K), $\dot{m}_f$ is the feed flow rate (kg/s), and $T_{f,i}$, T_{fo} the feed temperatures at the module inlet and the outlet (°C).

3.3. Gained output ratio (GOR)

The GOR is one of the most important criteria of industrialization of MD technology. The higher the GOR value is the better is the performance of the system. In MD pro-

Table 2
Operational parameters of solar-powered membrane distillation (SP-MD) systems

System	Bundoora, Australia	Gran Canaria, Spain	Gran Canaria, Spain	Alexandria, Egypt	Irbid, Jordan	Aqaba, Jordan	Freiburg, Germany	Almeria, Spain (PSA)	Almeria, Spain (PSA)	Hangzhou, South China	Xiamen, South China	Mahares, Tunisia
MD configuration	(Lab scale DCMD)	(compact PGMD[a])	(two-loop AGMD)	(compact AGMD)	(compact AGMD)	(two-loop AGMD)	(compact AGMD)	(two-loop AGMD)	(two-loop AGMD)	(compact VMD)	(compact VMD)	(two-loop VMD)
Operation year	2014	2006	2006	2005	2005	2006	2002	N/A[b]	2009	2006	2012	2011
Feed water source	NaCl solution	Seawater	Seawater	Brackish	Brackish	Seawater	Tap water	NaCl solution	NaCl solution	Brackish	NaCl solution	Seawater
Feed temperature (°C)	30–45	55–85	78	60–70	85	85	45–90	Up to 85	60–80	45–83	55–75	60–80
Feed flow rate (L/h)	300–600	300–420	~1650	300–480	250–440	1100	225	300–1200	1200	180	70–110	1200
Daily production (L/d)	N/A	75	1200	64	Up to 120	144–792	81	N/A	N/A	N/A	8	32–56
No. of daily solar radiations hours	10	11	12	12	9	10	10	N/A	8	9	8	10
Peak solar-irradiation (W/m^2)	700	1000	1100	995	998	1100	900	N/A	1000	1238	1070	1000
Membrane type	Flat sheet	Spiral wound	Spiral wound	Spiral wound	Spiral wound	Spiral wound	Spiral wound	Flat sheet	Flat sheet	Hollow fiber	Hollow fiber	Hollow fiber
Membrane material	PTFE	PTFE	PTFE	PTFE	PTFE	PTFE	PTFE	PTFE	PTFE	PP	PP	PVDF
Membrane area (m^2)	0.1074	8.5–10[c]	35–60[d]	N/A	10	40	8	2.8	9	0.09	0.25	4
Solar collector type	N/A	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	N/A	CPC	CPC	N/A	Vacuum tube	Flat plate
Solar collector area (m^2)	N/A	6.96	90	5.73	5.73	72	5.9	500	500	8	2.16	70
Thermal energy source	Salinity-gradient solar pond	Corrosion free solar thermal collectors	Solar thermal collectors	Corrosion free solar thermal collectors	Corrosion free solar thermal collectors	Solar thermal collectors	Solar thermal collectors	Solar thermal collectors	Solar thermal collectors	Solar thermal collectors	Solar thermal collectors	Solar thermal Collectors
Electricity source	Grid	PV	PV	PV	PV	PV	Grid	Grid	Grid	Grid	Grid	PV
Reference	[28,29]	[10,30]	[10]	[31,32]	[19]	[20]	[9]	[33]	[34]	[35]	[12]	This study

Adopted partially from [12] and [13]
[a]PGMD is the abbreviation of permeate gap membrane distillation, an enhanced configuration of DCMD.
[b]N/A = Not available.
[c]The membrane area was 8.5 m^2 at first, and then changed to 10 m^2.
[d]The MD unit had five modules, and each module had a membrane area of 7–12 m^2.
Notes: AGMD – air gap membrane distillation; DCMD – Direct Contact membrane distillation; PSA – Plataform a Solar de Almeria; and VMD – vacuum membrane distillation; and PV – photovoltaic.

cess, the GOR is a dimensionless parameter defined as the amount of thermal energy required to vaporize the mass of water produced to the thermal energy input actually provided by the system:

$$GOR = \frac{\dot{m}_d \cdot \Delta h_v}{Q_h} \quad (4)$$

where Δh_v is the latent heat of vaporization of water (kJ/kg).

3.4. Performance ratio (PR)

The PR is defined as the distillate flow rate, $\dot{m}_d$ divided by the external thermal energy input, Q_h:

$$PR = \frac{\dot{m}_d}{Q_h} \quad (5)$$

A high PR means that a high distillate flow rate is obtained per a given thermal energy input. Usually, a high PR can be achieved by using well-designed system components with high energy efficiency and good insulating material.

3.5. Recovery ratio (RR)

The RR is calculated by dividing the distillate flow rate, $\dot{m}_d$ by the feed flow rate $\dot{m}_f$:

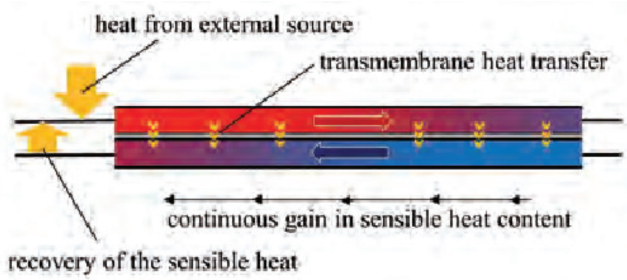
$$RR = \frac{\dot{m}_d}{\dot{m}_f} \times 100 \quad (6)$$

A high RR means that a relatively high distillate flow rate is obtained from a given feed flow rate. Generally, a low RR translates into increased specific energy (both thermal and electrical) consumption values.

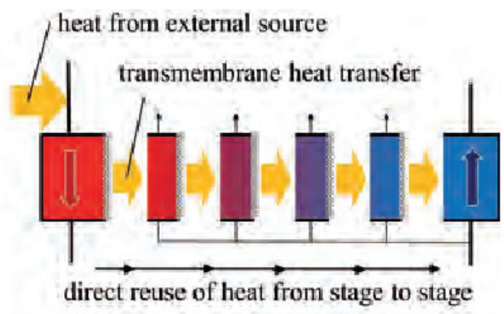
3.6. Energy recovery design

In MD processes, an enormous amount of heat is transferred through the membrane, mainly as latent heat but partially also from conductive heat transfer. The minimum heat requirement in the evaporator channel is given by the latent heat of evaporation that is essentially required for the desired phase change and consequently for permeate production. If the required thermal energy is produced exclusively for the MD process or a limited resource of available heat is used, the thermal energy has a certain value and thermal process efficiency becomes a crucial MD process specification defining its competitiveness and economic feasibility [36].

Therefore, the design and use of recovery systems should be optimized. The basic heat recovery concepts usually considered in MD may be categorized according to two principal approaches that are closely related to those established in conventional thermal desalination technologies: recovering the sensible heat of concentrated brine by brine recirculation, and recovering the condensation heat using feed solution in the condenser [12].The sensible heat recovery concept, illustrated in Fig. 2(a), is similar to the MSF approach, while the latent heat recovery concept, illustrated in Fig. 2(b), is similar to the MED approach.



(a) Sensible heat recovery (cf. MSF)



(b) Latent heat recovery (cf. MED)

Fig. 2. Basic heat recovery concepts suitable for MD applications [36]: (a) sensible heat recovery (cf. MSF) and (b) latent heat recovery (cf. MED).

4. Discussion and analysis

4.1. Performance results

Table 3 summarizes the performance indicators for the present study concerning the solar VMD plant with the reported and calculated values from published operational parameters of the previous SP-MD systems. As shown in this table, permeate fluxes in AGMD configuration are very low when compared to VMD systems with permeate flux from 14 to 32 $L/m^2 \cdot h$ which claimed to compete with RO where typical flux values range between 12 and 45 $L/m^2 \cdot h$ [37].

The maximum RR value of the solar VMD plant presented in this study is found to be 4.66% which lies in the higher range of RR obtained from previously tested SP-MD systems which showed values ranging from 0.25%–6.5%. However, RR values reported above can be considered very low compared to other seawater desalination techniques, since the RR values vary from 40% to 60% in RO and from 15% to 50% in MSF or MED [38]. This is mainly because MD systems operates in single stage. Therefore, increasing the number of stages would improve the RR of the system.

Recently, MEMSYS (Germany) have commercialized a relatively new MD technology that combines the advantages of multi-effects and vacuum to achieve highly efficient heat recovery as compared with traditional MD processes [39]. This technology, known as vacuum multi-effect-membrane distillation (V-MEMD), was tested in the demonstration plant at Marina Barrage, Singapore [40]. The membrane module consists of four evaporation-condensation stages and each stage recovers the heat from the previous stage. Seawater is introduced to

Table 3
Performance indicators of solar-powered membrane distillation SP-MD systems

System (configuration)	Bundoora, Australia (DCMD)	Gran Canaria, Spain (compact PGMD)	Gran Canaria, Spain (two-loop AGMD)	Alexandria, Egypt (compact AGMD)	Irbid, Jordan (compact AGMD)	Aqaba, Jordan (two-loop AGMD)	Freiburg, Germany (compact AGMD)	Almeria, Spain (PSA) (AGMD)	Almeria, Spain (AGMD)	Hangzhou, South China (VMD)	Xiamen, South China (VMD)	Mahares, Tunisia (VMD)
Maximum flux (L/m²·h)	2.2	1	3	1	1.5	1.5	1.44	7	3.23; 5.09[b]	32	14.4	14
Recovery ratio (%)	0.4–0.5[a]	1–3.5[a]	4–5[a]	0.5–2[a]	4–4.5[a]	2–5	3.5–6.5[a]	0.25–1.3	0.3–1.8; 2.2–4.5	0.25–1.5[a]	3.3–5[a]	2.66–4.66
Performance ratio (kg/MJ)	0.3–0.35[a]	0.1–0.85[a]	N/A	0.3–1.5[a]	N/A	0.2–0.3	N/A	0.28–0.79	0.2–0.3; 1.5–1.7	N/A	0.37[a]	0.54–0.95
Gained output ratio	1.1–1.25[a]	3–6	3–6	0.97[a]	0.3–0.9	0.4–0.7	2–3.1[a]	0.8	0.7–1; 5.2–5.6[a]	0.85[a]	1.27[a]	1.9–3.3
Specific thermal energy consumption (kWh/m³)	780–900	140–350	180–260	N/A	200–300	200–300	N/A	810–2200	2100–3250; 380–425[a]	7850	750	290–510
Reference	[28,29]	[10,30]	[10]	[31,32]	[19]	[20]	[9]	[33]	[34]	[35]	[12]	This study

[a]Values calculated using reported data
[b]The first data is for prototype A (compact module), and the second data is for prototype B (three modules connected in series)
Notes: DCMD – Direct Contact membrane distillation; PGMD – permeate gap membrane distillation; AGMD – air gap membrane distillation; PSA – Plataform a Solar de Almeria; and VMD – vacuum membrane distillation; PV – photovoltaic; and N/A = Not available.

the first stage and flows serially through the remaining stages which allows more distillate to be produced at each stage. RR ranging from 60 to 80% were attainable for the V-MEMD unit.

As for the PR of the solar VMD plant, it is found to be within the range from 0.54 to 0.95 kg/MJ which is far lower than those for MSF or MED processes where typical PR are between 1.7 and 6.4 kg/MJ [41]. The low PR could be alleviated if multi-staging of MD is applied. Liu et al. [42] developed a multi-effect membrane distillation (MEMD) process based on hollow fiber AGMD module with a capability of internal latent heat recovery. Such a process has two distinct characteristics: (1) the evaporator tubing (usually porous hydrophobic hollow fiber) is exactly in parallel with the condenser tubing (nonporous hollow fiber) so that the cold-feed and the hot-feed are strictly counter-current, and, thus, the condensation heat is recovered at maximum; (2) unlike the discrete segments or cascades in MEMD configurations, this simple once-through module in reality has a continuum of stages/effects to achieve a high PR value (up to 3.35 kg/MJ).

The dispersion of the GOR values of the studied solar VMD plant is in the range of 1.9–3.3 which is relatively high compared to most experimental MD systems showing values of GOR less than unity indicating low MD performance. However, the GOR values obtained are low when compared to other mature thermal desalination technologies like MED with a GOR of about 8–16 [43]. Placing multiple modules in series would improve the GOR of the system and the overall efficiency. Gilron et al. [44] pointed out that the highest GOR for a standalone cross-flow DCMD module with external heat recovery would be no more than 2.2, and also predicted via simulations that the GOR could potentially reach as high as 12 by combining these modules into a counter-current cascade as a single block. Experiments were further carried out by Lee et al. [45] using cascades consisting of 2–8 DCMD stages in conjunction with heat exchangers. The highest reported experimental value of GOR was between 5 and 6.

A higher GOR value can also be achieved using high membrane areas because of the increase of the water production as indicated in the literature [44]. However, higher capital costs are required for providing more membrane elements. Additionally, larger membrane areas do not always lead to higher GOR which is the case for the solar desalination systems developed by Fraunhofer ISE (Germany) [46]. A theoretical study carried out by Zuo et al. [47] based on simulation of a DCMD system in Aspen Plus platform, has been focused on the influence of the design and operating parameters on the GOR value, including the membrane area. It was observed a significant enhancement of water production and the GOR with increasing membrane area below a critical value (i.e. 4 m^2), after which the effect of the membrane area on water flux and the GOR was limited.

Regarding the STEC, all SP-MD systems presented here show high consumption values (generally higher than 200 kWh/m^3) compared with commercial thermal desalination processes such as MED which have a thermal energy consumption in the range of 40–65 kWh/m^3 [33]. This is mainly due to high process inefficiency of MD. Therefore, energy recovery is needed for reduction in the STEC to be achieved. Operating without energy recovery, the STEC value of the solar VMD system tested in Hanzagho-China [35] is high as 7850 kWh/m^3. By recycling the concentrated brine as feed, the STEC of the solar VMD system developed in Xiamen-China [12] is found to be lower (around 750 kWh/m^3).Duong et al. [48] applied the brine recirculation to optimize the thermal efficiency of seawater desalination by DCMD system. The results showed that the STEC of the system could be reduced from 4500 to about 1900 kWh/m^3 (more than half) when the recirculating flow is set at 50% of the feed flow. Nevertheless, the achieved thermal efficiency of the DCMD system is still lower compared to those reported in the MD literature [49]. By recovering the latent heat of condensation, our system and those in [35] and [12] obtained much lower STEC values, 290–510 kWh/m^3. The heat recovered quantity by condensation depended on the vapor temperature level and thus on the membrane module configuration (number of compartments per module, number of passes, etc.). This quantity represents in reality the fraction of the condensation heat recovered. Running as a simple cycle (without energy recovery), the heat the STEC is equal to the evaporation latent heat. Thus evaporating 1 kg of water requires 0.58 kWh ($\Delta h_v = 2.1 \times 10^6$ J/ kg ≈ 580 kWh/m^3). Recovering 50% of the condensation heat, the STEC is equal to 290 kWh/m^3 (i.e., 0.29 kWh per kg of distilled water). It is worth mentioning that, using both ways of energy recovery further lowered energy consumption as is the case of the compact system in Gran Canaria, Spain [10,30] which had the lowest STEC, 140–350 kWh/m^3, among the systems listed.

Another attempt to minimize the STEC has been made in the solar-powered AGMD system (prototype B) tested at Plataforma Solar de Almeria (PSA), Spain [34]. Three modules were connected in series and counter-current mode, each of them with a membrane area of 3 m^2. Hot feed water is routed to the MD modules, where the evaporation took place. The cooled water evacuated from the hot side (evaporator) of the first module is sent to the cold side (condenser) of the second module. This water on the condenser side recovers the heat of condensation from the second module and then enters the evaporator side of the third module. At the same time, the cooled flow of water on the evaporator side from the second module is used as refrigerant for the third module and so on. The evaporator and condenser flows are therefore interchanged through the system. Experimental results indicated that distillate production increases 25% from 1 to 3 modules in series, while the STEC is reduced from 1226 kWh/m^3 to 425 kWh/m^3 (more than 65% heat saving) by recovering the latent heat of condensation and also the sensible heat transferred by conduction from the hot side of the membrane. However, STEC of the system is still very high. A comprehensive review and assessment of SP-MD systems is presented in [13,50].

4.2. Parametric study

In this study, the variation in GOR, a key performance indicator, was evaluated by varying the feed mass flow rate, the feed inlet temperature, the vacuum pressure, and the solar collector area. The baseline parameters for the simulations are given in Table 4. Each of the parameters are varied around their baseline value keeping the other variables constant to understand their effect on the GOR.

Fig. 3 shows the effect of feed mass flow rate on GOR. It can be seen that GOR decreases exponentially with an increase of the mass flow rate. In general, the increase in feed mass flow rate leads to the improvement of the transfer of heat and mass in the membrane following the increase of the distillate flow rate. However, this raises the heat and mass transfer resistance in the air gap, leading to the requirement of a greater temperature difference between the feed and coolant. Additionally, the same solar array has to heat more mass leading to a decrease in top temperature, this effect quickly overwhelms the increase in flux from more efficient heat transfer, resulting in a net decrease in flux for a given amount of heat input.

Fig. 4 shows the variation of the GOR with the inlet feed temperature. As observed, GOR increased with increasing feed temperature. This occurs because higher feed temperatures improve the membrane permeability and increase the potential for vapor flux as a result of the increase in feed-side water vapor pressure. Despite the higher amount of heating energy required at the higher temperatures, it seems that this effect has less impact on the GOR values, and hence it is highly recommended to raise the feed inlet temperature to the highest value possible. However, the membrane inlet temperature should not exceed 80°C for the structure of membranes cannot resist high temperatures that can cause an alteration of their mechanical strength [25].

Fig. 5 shows the effect of the applied vacuum pressure on the GOR. The GOR increases with the increase of the pressure gradient which is the driving force of the mass transfer. Reduced pressures enable the evaporation of seawater at relatively low temperatures, which increase the distillate production. However, the risk of membrane pore wetting becomes very high with the decrease of the vacuum pressure as a result of an increase in the trans-membrane hydrostatic pressure difference. Thus, it is recommended to operate the VMD system at moderate degree of vacuum.

Finally, GOR increases linearly with an increase in the solar collector area (Fig. 6). By increasing the area of the solar collector in order to obtain higher solar fraction, the vapor pressure difference across the membrane becomes higher due to the increase in the feed top temperature, thereby providing for more permeate flux.

Table 4
Baseline values of the solar vacuum membrane distillation (VMD) plant

Variable	Value	Unit
Feed mass flow rate	1200	kg/h
Feed inlet temperature	65	°C
Vacuum pressure	15	kPa
Solar collector area	70	m^2

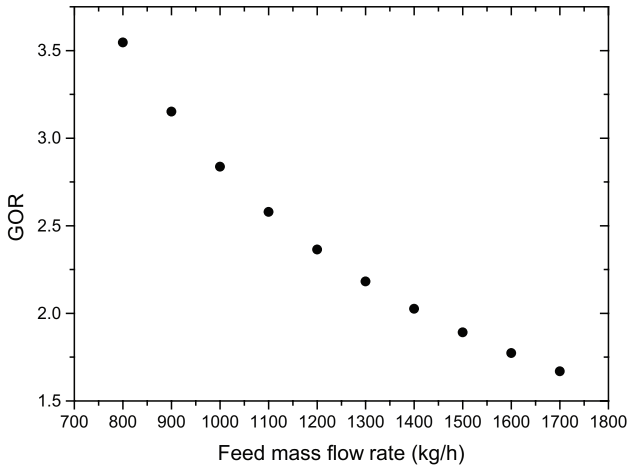


Fig. 3. Gained output ratio (GOR) dependency on feed flow rate.

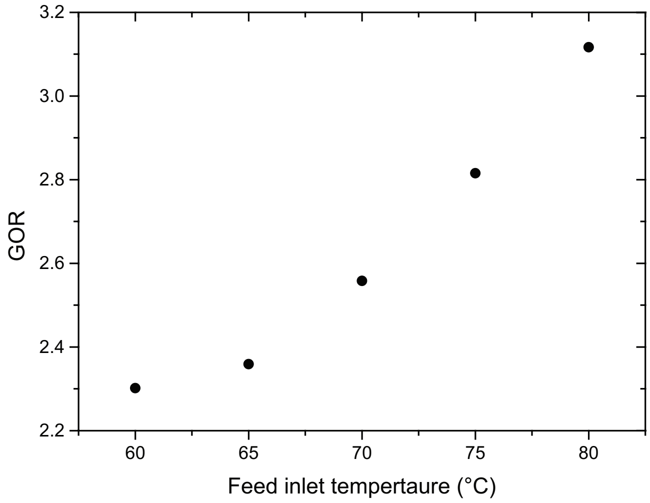


Fig. 4. GOR dependency on membrane inlet temperature.

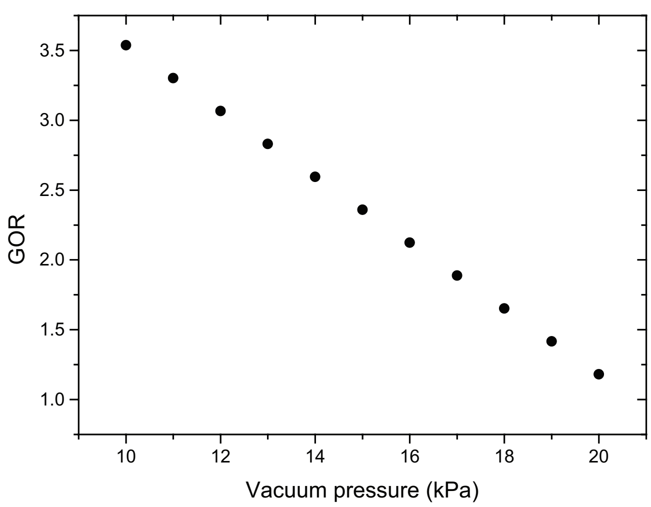


Fig. 5. GOR dependency on permeate pressure.

5. Cost estimation

The water production cost (WPC) can be determined using the following expression:

$$WPC = \frac{C_{tot}}{fQ_{p,d}365} \quad (7)$$

where f is the plant availability and $Q_{p,d}$ the plant capacity.

The total annual cost, C_{total} is the sum of annual fixed charges, C_{fixed}, operating and maintenance (O&M) costs, $C_{O\&M}$, and membrane replacement cost, $C_{m,repl}$.

$$C_{total} = C_{fixed} + C_{O\&M} + C_{m,repl} \quad (8)$$

The annual fixed charges, can be estimated using the following equation:

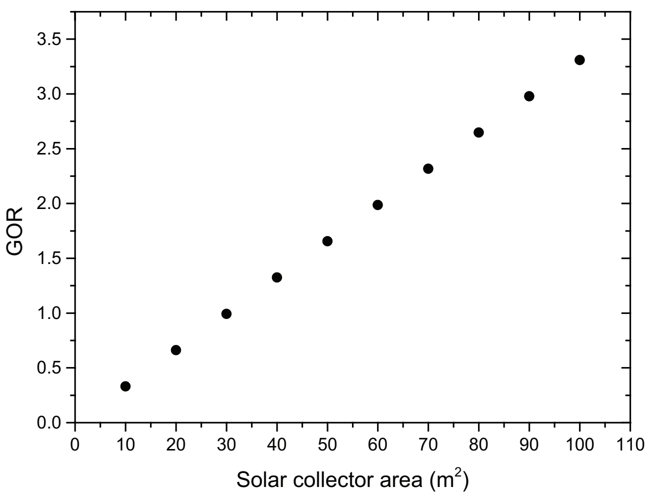


Fig. 6. GOR dependency on solar collector area.

$$C_{fixed} = aCC \quad (9)$$

The amortization factor, a is given by:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10)$$

where i is the annual interest rate and n is the lifetime of the plant.

The total capital cost, CC covers purchasing cost of equipment, instrumentation and control, land, installation charges and pretreatment of water.

The capital, operating and total annual costs of the solar VMD plant are analyzed according to the following assumptions [51]:

- The installation cost represents 25% of the purchased equipment costs.
- The instrumentation and control cost is equivalent to 25% of the total purchased equipment cost.
- Zero land cost (land is offered by the state).
- Zero pretreatment cost (chemical pretreatment of the water supply is not necessary).
- The annual interest rate, i, and plant lifetime, n, for amortization of the capital cost are 5% and 20 years.
- The plant availability factor, f, is assumed to be 0.9 (90%).
- The annual O&M costs, $C_{O\&M}$, are estimated at 20% of the plant annual fixed charge.
- The annual rate of membrane replacement is 20%.

The equipment costs are determined from the cost functions listed in Table 5. Table 6 gives the capital expenditure items and the estimated cost of potable water produced by the solar VMD plant. In this study, the unit cost with a 1:1 dilution of the pure water produced is used for comparison with the production costs from other SP-MD systems as shown in Table 7.

Table 5
Cost function for equipments

Equipment	Purchased cost ($)	Reference	Note
Membrane module	$C_{MD} = 410 \times A_m$	[52]	PVDF membranes
Plate heat exchanger	$C_{HX} = \left[363.56 + 8.54\left(\frac{A_{HX} - 1}{0.032}\right)\right]F_M$	[52]	1 m$^2 \le A_{HX} \le$ 5 m^2; F_M = 4.7 (titanium plates)
Tubular condenser	$C_{cd} = 2467.2\left(\frac{A_{cd}}{0.51}\right)^{0.024}$	[53]	Fixed tube sheet design (titanium tubes); 0.2 m$^2 \le A_{cd} \le$ 10 m^2
Solar collector	$C_{sc} = 890.78\left(\frac{A_{sc}}{5.73}\right)^{0.9}$	[52]	With rack
Storage tank	$C_{TK} = 165\left(\frac{V_{TK}}{1000}\right)^{0.57}$	[52]	Carbon steel
PV module	$C_{PV} = 5P_{PV}$	[51]	η_p = 0.75 (feed pump and circulator);
Pump	$C_{PP} = 501 \times \eta_p P_{PP}$	[54]	η_p = 1 (peristaltic pump)

It can be observed that the WPC obtained for the solar VMD plant ($15.5/m^3) is within the same order of magnitude of SP-MD systems cited in the literature which varies from 10 to $36/m^3. However, the cost of produced water is relatively high compared to other mature solar desalination technologies such as PV–RO process which costs between $2–13/m^3 [58–60]. This is mainly due to the high initial capital investment. In fact, such high costs are expected when using solar collectors needed for heating water and PV panels to ensure the installation autonomy in electrical energy. Thus, the part of solar energy cost contributes around 73% of the total equipment cost as seen in Fig. 7.

Table 6
Cost results for the solar vacuum membrane distillation (VMD) plant

Item	Value
Membrane module ($)	1640
Plate heat exchanger ($)	1809
Tubular condenser ($)	2468
Solar collectors ($)	8473
Storage tanks ($)	250
PV module ($)	10500
Pumps ($)	814
Total equipment costs ($)	25954
Installation ($)	6488
Instrumentation and control ($)	6488
Total capital cost ($)	38931
Annual fixed cost ($/y)	3124
Membrane replacement cost ($/y)	328
O&M annual cost ($/y)	625
Total annual cost ($/y)	4076
WPC ($/m^3)	31
WPC with 1:1 dilution ($/m^3)	15.5

Notes: PV – photovoltaic; O&M – operating and maintenance; and WPC – water production cost.

Fig. 8 depicts the effects of potential savings in the cost of system components of the solar VMD plant on the WPC. This figure was generated by applying a percentage reduction on the cost of one component at a time to study its effect on the overall WPC. As expected, of all components, the cost of solar technology contributes, by far, the most important impact on produced water cost. However, it is should be noted that the cost contributions of solar collectors and PV panels are likely to decrease significantly in future as new technologies enmerge.

Economies of scale are also likely to lead to cost reductions for solar technologies given the expected growth in MD desalination capacity. The effect of increasing water production rate of the solar VMD plant on the WPC is shown in Fig. 9. It can be clearly seen that by increasing the plant capacity, the cost of water decreases considerably. For example, when the distillate mass flow rate is 40 kg/h, the cost of distillate production is $15.5/m^3. However, when the distillate mass flow rate is assumed to be 100 kg/h, the cost of distillate production drops to approximately $6/m^3.

Another possible solution to decrease the WPC of SP-MD systems is to restrict the reliance on solar energy to

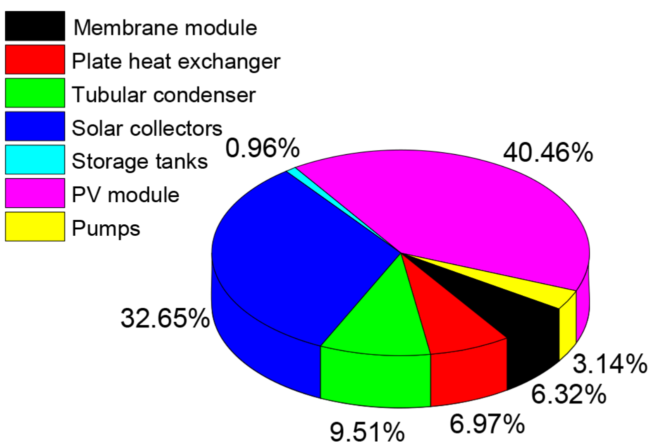


Fig. 7. Proportion of purchased equipments cost.

Table 7
Estimated water production cost (WPC) of different solar-powered membrane distillation (SP-MD) systems

System (configuration)	Capacity (L/d)	Water production cost ($/m^3)	Reference
Solar-driven DCMD plant	500	10–15	[55]
Solar-driven AGMD plant	73	15.67–31.34	[56]
Compact AGMD solar-driven plant	100	15–29.9	[19]
Large AGMD solar-driven plant	500	18–36	[20]
Two-loop AGMD solar-driven plant	100	15.7	[50]
Solar-driven DCMD	700	12.7	[57]
Solar-driven AGMD	700	18.26	[57]
Solar-driven VMD	700	16.02	[57]
Solar-driven VMD plant	400	15.5–31	This study

Notes: DCMD – Direct Contact membrane distillation; AGMD – air gap membrane distillation; and VMD – vacuum membrane distillation.

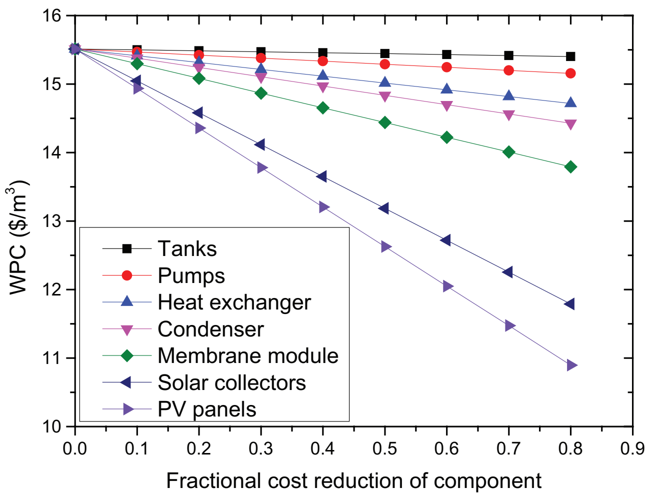


Fig. 8. Effect of cost reduction of the solar VMD plant component on the WPC.

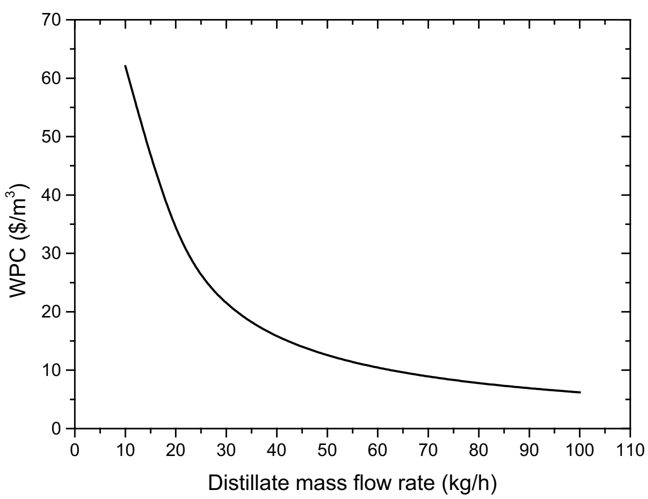


Fig. 9. Effect of water production rate on the WPC.

electric power generation while using other sources of heat, especially waste heat recovery from industrial processes, for water heating such as thermal desalination plants with hot brine, power plants, etc. [13,57]. Table 8 show the resulting WPC of the solar VMD plant without PV module and solar collectors. It is clearly seen that the actual cost of water production could be greatly reduced if inexpensive waste heat would be available.

Table 8
Estimation of water production cost (WPC) with different set-ups

Water production cost	($/m^3)
With PV module and solar collector	15.5
Without PV module	9.8
Without PV module and solar collector	5.1

Notes: PV – photovoltaic.

6. Conclusion

The main objective of this study was to assess the overall performance of an autonomous solar VMD plant for seawater desalination with comparative analyses against the published results of other SP-MD systems. The implementation of the pilot plant was carried out in a village of orphans in the coastal region Mahres (Tunisia) as part of the European project MEDINA. Performance analysis has been conducted based on different indicator parameters, including RR, PR, GOR and STEC.

The obtained results indicated that VMD process can compete with RO on permeate flux with approximately the same water production. However, the RR of the VMD process is very low which result in an increase of the STEC. Similarly, low values of PR and GOR were achieved. Therefore, the design and use of heat recovery systems is an important aspect for achieving sustained reductions in energy consumption. This study has shown that the recovery of the latent heat of condensation enabled significant energy savings. This is also possible through multi-staged MD effect. However, cost analysis is needed to verify if multi-staging is favorable.

The effect of various operating parameters such as feed flow rate, feed inlet temperature, vacuum pressure, and solar collector area on the GOR, as a key system performance, was investigated. The parametric study showed that high GOR values can be achieved at low feed flow rate and high feed temperatures. Moreover, the GOR increases with an increase of the applied vacuum level and the solar collector area. However, it is important to note that all of these parameters should be optimized not only on the basis of performance enhancement but also by considering technical and economic constraints.

Finally, an economic analysis was performed to evaluate the WPC of the solar VMD plant. Based on calculations, the estimated WPC was found to be \$15.5/m^3 which is nearly similar to the values obtained from SP-MD systems reported in the literature. However, these costs are much more expensive than that produced from commercial solar-powered desalination plants. This is mainly due to the high initial capital investment, especially the cost of solar collectors and PV panels which make up more than 70% of the total system cost. Nevertheless, it must be taken into consideration that the cost contributions of solar technology are projected to decrease in the next coming years due to economy of scale for large water production capacity. Moreover, it is expected that the WPC could be further reduced by restricting the reliance on solar energy to electric power generation while using cheaper waste heat when available.

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