Solar photovoltaic-powered membrane distillation as sustainable clean energy technology in desalination

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The present article discusses the application of a new technology using solar photovoltaic (PV) cell coupled with membrane distillation (MD) in the desalination of tap water. Salinity decreases the palatibility of water and causes long-term health issues. MD is the most promising technology to provide safe and clean drinking water to households and for other applications in small quantities. It consumes less energy than the existing commercial brackish water reverse osmosis (RO; pressure-driven) desalination technology (48%) used for the production of drinking water. A large population in India relies on tap water, groundwater, surface water, deep well water and municipal water for drinking and domestic utilization. These sources are highly contaminated due to the presence of harmful metals like fluoride and arsenic causing serious health hazards. The present study compares water quality analysis by chemical methods of both RO and solar PV-driven MD technology. The quality of distillate obtained by MD is excellent and this has been proved by the results of chemical analysis of water. Thermal efficiency of MD operating with solar PV cells and others operated purely by conventional mode is calculated and the results are compared. The study shows higher production of drinking water for solar PV-driven MD.

Keywords: Clean energy technology, desalination, membrane distillation, solar photovoltaic cells, thermal efficiency.

THE growing scarcity of freshwater around the world poses a great threat to human survival. The present constituents of earth's water resource are ocean and sea water – 96.5%; ice caps – 1.7%, while the remaining are brackish and slightly salty surface waters in estuaries[1]. Water sources currently available on earth are not potable as their total dissolved solids (TDS) content is above 500 ppm, which is not potable according to the WHO standards. So there is an immediate need to device methods to reduce dissolved salt content from these available water sources and make them suitable for human consumption. The removal of dissolved salt from sea water is mainly through desalination techniques like conventional thermal distillation or membrane separation. Conventional thermal distillation methods like multistage flash distillation (MFD), multi-effective distillation (MED) and mechanical-vapour compression (MVC) consume higher thermal energy and cause environmental hazards like emission of carbon dioxide into the atmosphere. Membrane separation techniques like reverse osmosis (RO), micro filtration, ultra filtration, nanofiltration, membrane distillation (MD), etc. are used for water purification technology. RO and MD are commonly used for desalination of sea water, brackish water, groundwater and other salty surface water resources. RO is the most popular among the existing commercial membrane technologies for the desalination of sea water. The disadvantages of RO are high operating pressure, high energy consumption, brine disposal problems, environmental hazards, fouling of membrane and challenges in development of small units in rural areas where infrastructure and grid facility are lacking. This has led to the introduction of new technologies like MD. The advantages of MD are low operating temperature (below the boiling point of water), no brine disposal problems, durability of membrane (hydrophobic), and being feasible for small-scale processes in rural communities. Renewable energy like solar energy is abundant in arid and semi-arid regions. Hence to make the desalination method more viable for low production requirement and environment-friendly, application of renewable energy integrated with thermal-driven MD is found to be more attractive. Solar photovoltaic (PV) powered MD can be utilized as an alternative new technology in desalination of drinking water exclusively for low-scale processes in rural areas. The energy requirement for RO is 4 kWh/m^3 for 5–10 l/m^2 h

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at 20°C and for MD (vacuum MD) it is 1.5 kWh/m^3 for 120 l/m^2 h and 1.3 kWh/m^3 for 85 l/m^2 h at 25°C (ref. 2).

Renewable energy

Water and energy are the basic needs for humans. Currently renewable energy is an effective solution for the global crisis of water and energy. Solar, wind, ocean, tidal, geothermal energy, fuel cells, etc. are considered renewable energy as they can be replenished throughout the year. Due to depletion of conventional energy sources like fossil fuels, renewable energy is in greater demand. In order to achieve a sustainable future, it is crucial to develop this environment-friendly technology over the existing commercial desalination technology which causes environmental impacts like emission of greenhouse gases (GHGs) and brine disposal problems.

Population growth, economic performance and technological developments are significant factors in the determination of future energy consumption pattern. For long-term sustainable development and to overcome the environmental issues that we face today, renewable energy offers the best solution due to energy saving, economic viability and clean energy. Historical data conclude the existence of strong bond between energy availability and economic activity[3].

Solar energy insolation worldwide is 3–7 kWh/m^2/day. In India[4], average insolation during the least sunny day is 5.5 kWh/m^2/day. The remarkable progress in the contribution of renewable energy in the Indian power sector portfolio during the last three decades is proof of the enormous scope and opportunities in clean energy technologies, especially in solar energy[5].

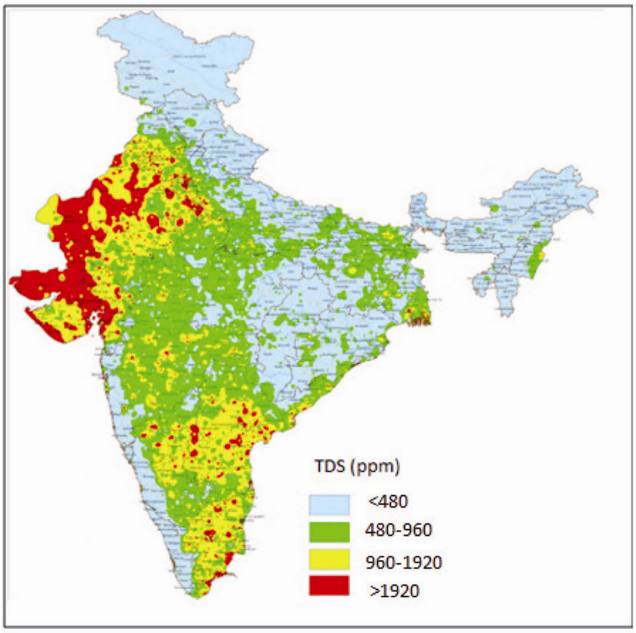

Figure 1. Map of salinity levels in Indian groundwater. [Source: Central Ground Water Board, Ministry of Water Resources, Government of India; http://cgwb.gov.in/documents/water_quality/gw_quality_in_shallow_aquifers.pdf]

Groundwater condition in India

Wright *et al.*[6] have found the electrodialysis (a new desalination technology), powered by solar PV panel would be more effective for desalination in the rural areas of India. According to their study, 60% of land area in India has salinity level greater than 480 mg/l. Figure 1 shows a map of the salinity levels of groundwater across various states in India[6].

Membrane-based desalination by solar energy

Desalination is the removal of salts and minerals present in the feed solutions and improving the palatability of saline water to potable and high quality distilled water. Desalination of water can be done using two approaches: thermal method and membrane process. Membrane separation of saline water can be thermal-driven, pressure-driven, or voltage-driven. RO is a pressure-driven membrane technology commercially dominating desalination of sea and brackish water resulting in high energy consumption and environmental impacts. MD is a thermal-driven process used for desalination of all types of water resources. Feasibility, high-quality distilled water production, use of low temperature, and no pollution are attractive features of MD over RO membrane technology.

MD can be coupled with solar energy for desalination of various water resources. Solar energy can drive the desalination units by either thermal energy from solar thermal systems or electricity generated by PV systems. Studies have shown that low cost makes the solar PV-driven desalination process a technically cost viable system for freshwater production in remote areas over a period of five years due to an increase of fossil fuel prices[7].

In rural areas with scarcity of potable water, it is necessary to revive the alternative low-carbon technologies based on renewable energy sources for safe drinking water production. Solar energy is found to be one of the most promising renewable energy sources for desalination process as most of the commercial desalination technologies available today consume high-grade energy generated through conventional non-renewable energy sources[8].

Solar thermal energy is used for direct applications in water distillation. The main cost is during the initial investment. However, once the system is operational, it is extremely cheap to maintain. There are two types of solar thermal energy systems: (i) solar thermal-assisted systems and (ii) solar PV assisted systems.

Solar thermal-assisted systems

A solar thermal-assisted system works on the principle of using natural solar pond/solar still and a concentric mirror. It is classified into direct and indirect solar thermal desalination systems.

Direct solar thermal desalination: This is mainly suited for small production systems, such as solar stills, in regions where the freshwater demand is low.

Indirect solar thermal desalination: This method uses solar energy to produce distillate indirectly using a concentric or parabolic mirror. The conventional thermal desalination processes are MSF, MED and MVC coupled with solar collector and solar pond which produce high-quality distillate. Salinity gradient solar ponds act as a type of heat collector and heat storage[9].

Solar photovoltaic-assisted systems

These constitute PV cells which convert solar energy into direct current (DC). Among the solar energy hybrid systems available, solar PV-driven MD technology is economical and technically feasible[10].

The PV system consists of a number of PV modules, equipment like batteries, charge controller, DC/AC inverter, etc. producing output electric power by efficient use of solar energy. The whole system can be integrated with the membrane desalination unit. Solar PV electricity system is one of the most significant renewable energy technologies because of its potential future uses. It is a promising technology to meet the future energy demands and environmental issues. The salient features of PV systems are the reduction in CO_2 emission, no moving parts, low operation and maintenance[11].

The efficiency of a solar PV cell can be considered as the ratio of the electricity generated to the global solar irradiation. Power conversion efficiency is ratio of the area under the current voltage characteristic curve of a PV cell divided by the input illumination intensity and the available area. Solar PV and thermal applications appear to be potential solutions for current energy needs and to combat GHG emissions[12].

Integration of solar energy with membrane system for desalination of sea water or brackish water is considered to be an alternative and effective way for drinking water production exclusively in the rural and arid areas where grid connection is limited[13].

Membrane distillation

MD for water desalination is a thermally driven membrane-based technique, in which only vapour molecules are transported through hydrophobic micro-porous membranes. Under conditions of non-wettability vapour migrates through the pores of the membrane due to pressure difference created by the temperature difference on both sides of the membrane. Thus the hydrophobic membrane prevents the passage of liquid due to surface tension and allows only vapour to pass through it. Thermally driven MD is a new process that is being studied as a low-cost, energy-saving alternative compared to conventional separation processes like distillation and RO.

Desalination is a major application of MD and the configurations commonly employed are direct contact (DCMD), air gap (AGMD) and vacuum (VMD) membrane distillation. MD can operate with low-grade thermal energy. In solar-driven MD desalination system, either thermal or electrical energy supplied by flat-plate solar thermal collectors and PV panels has been studied with regard to many important aspects, including the feasibility, design of membrane distillation module, energy consumption and economic analysis and found to be a viable desalination technology[14].

MEDSOL sea-water desalination is an innovative solar-powered membrane distillation system project. The basic concept of this project is coupling MD with solar energy for freshwater supply in arid and semi-arid regions[15].

Memstill combines MFD and MED modes into a single air-gap membrane distillation module to improve the economy and ecology of existing desalination technologies for sea water and brackish water. Using low-grade waste steam or heat as the driving force, this process reduces the desalination cost to US$ 0.26 m^{-3} (ref. 16).

RO is a popular technology for the production of freshwater. Because of the technology evolution for the past 50 years, the production cost of freshwater has significantly reduced from US$ 5–10/m^3 to less than US$ 1/m^3. Even then, this technology is not economically viable in remote arid areas due to lack of infrastructure. The best available solution appears to be small passive solar stills for remote areas[17].

Advantages

MD has several advantages compared to conventional thermal distillation and RO processes. In MD, water is transported through the membrane only in a vapour phase; so it can offer complete rejection of all non-volatile constituents in the feed solution, ions, dissolved non-volatile organics, colloids and pathogenic agents. Hence, high-quality water can be obtained via the MD process at low temperatures. Membranes provide the highest level of treatment recommended by physically rejecting pathogenic microorganisms upstream of any post-disinfection such as UV[18].

Materials and method

The type of MD used here is direct contact MD, i.e. the steam produced is in direct contact with the membrane.

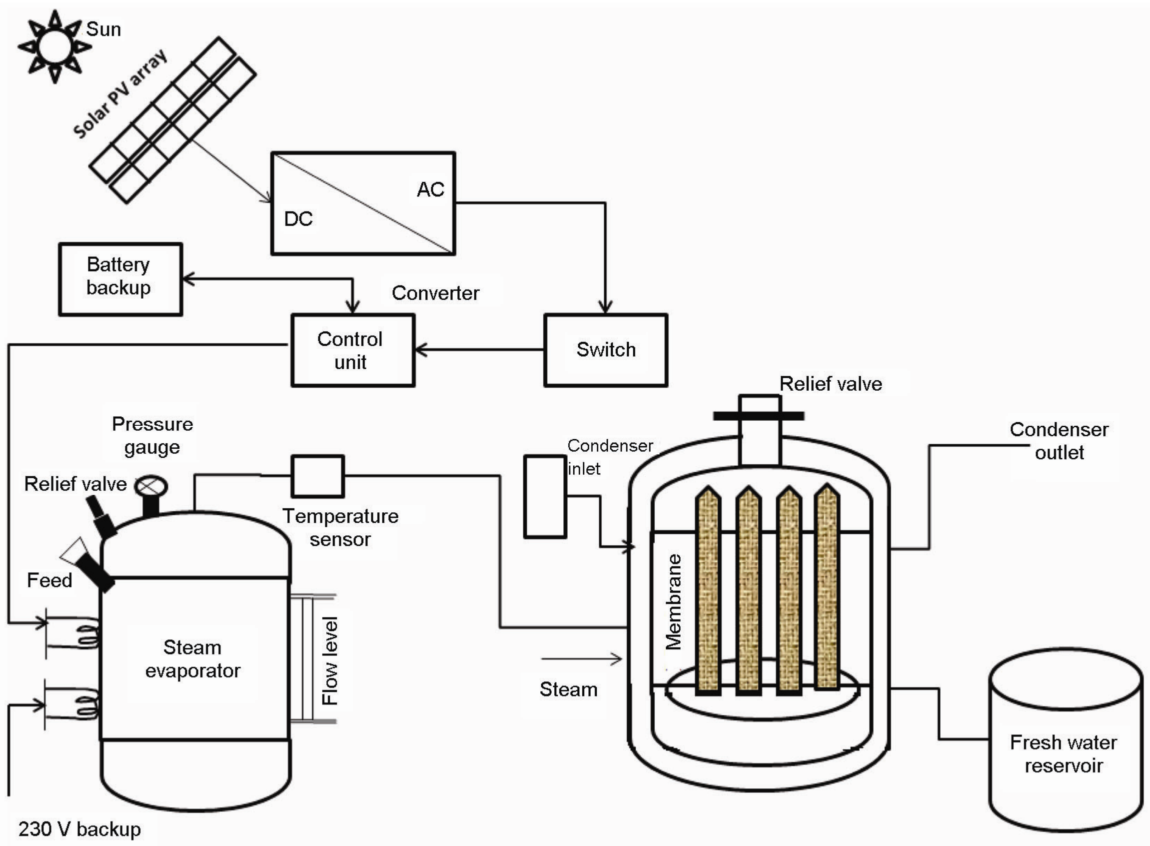

Figure 2. Schematic diagram of solar photovoltaic powered membrane distillation unit.

The tap water with TDS of 323 ppm was desalinated to high-quality distillate using solar PV-driven. The material used is PTFE (polytetrafluroethylene) membrane (Trinity Technologies Ltd, Mumbai). Effective membrane area of PTFE is 5.6 m^2 as provided by the manufacturer. The principle behind this experiment is as follows: the feed is in direct contact with the hot membrane side surface, evaporation takes place at the feed-membrane surface and the vapour is moved by the pressure difference across the membrane to the permeate side and condenses inside the membrane module. The hydrophobic membrane is used as a barrier for the removal of contaminants based on the mass transport of vapour driven by difference in vapour pressure. Thus it involves the hybrid process of thermal phase change with effective membrane separation of dissolved salts present in the feed water. The same procedure is used for conventional MD by supplying 230 V alternating current without the use of solar PV cells. The results are compared for both the experimental trials. DCMD is the simplest configuration capable of producing reasonably high flux. It is best suited for applications such as desalination in water production and concentration of aqueous solutions in food industry. Figure 2 shows schematic flow diagram. Tap water is used as feed and membrane distilled water as receiving phase. Specifications of membrane used are given in Table 1.

Solar PV powered MD unit

The experimental procedure utilizes the electricity generated by solar PV application. The preliminary step used for installing solar PV-driven MD is integrating the solar PV array unit to thermal MD. The solar unit consists of 10 PV modules, each producing 100 W power; the energy produced by the PV array is transferred through DC/AC charge controller to a battery capable of storing enough energy for intermittent operation. The stored energy is then transferred to the control unit through the DC/AC inverter. Thus the solar PV cell is integrated to the MD module (DCMD), producing a design capacity of 150 l/day. In this experiment, approximately 30 l of tap water (TDS, 323 ppm) was fed into 50 l capacity of steam evaporator equipment and heated at constant temperature of 368 K. The apparatus is well insulated for prevention of heat loss to the environment when the steam passes through the pores of the membrane, there is vapour pressure difference across the membrane, and this steam condenses on the permeate side of the membrane. Permeate temperature measured at the distillate side was 328 K. At constant feed rate, the volume of distilled water collected with known time intervals was measured to obtain permeate flux data. The experiment was started at 8 a.m. and steam was produced after 3 h; water was collected till

Table 1. Design specification of membrane distillation

Membrane distillation	Solar PV cell module
Membrane specifications	Design specifications
Media: 0.2 μm	Maximum power: 100 wp
PTFE: eight cartridges, hydrophobic	Voltage at maximum power: 17.40 V
Support media: polypropylene	Current: 5.75 A
Cage/core/endcaps	Normal operating cell temperature: 45°C
Gasket: silicon	Temperature coefficient of maximum power: 41%
Internal support ring: stainless steel	Number of PV cell modules used: 10
Dimensions	Dimensions: 1320 × 650 × 34 mm
Nominal length: 9.75 in	Weight: 10 kg
Outside diameter: 2.7 in	Solar cells: 36 cells in series
Inside diameter: 1 in	Constructions: high transmission low iron tempered glass, EVA, TPT
Operating conditions	
Maximum pressure difference:	Frame: anodized aluminum mainly for improving corrosion resistance
4.1 bar at 20°C	Colour: silver
2.1 bar at 60°C	Tubular battery: 12 V, 150 Ah

Figure 3. Photographs of solar PV powered membrane distillation components.

5 p.m. and the solar intensity was high around 11 p.m. Performance test has been done for many experimental runs with different water sample sources. Results are discussed based on the comparison of permeate flux, volume of product of distillate and thermal efficiency for solar PV cells coupled with DCMD module and for the conventional module which does not use solar energy. The main components for the design of solar PV powered MD unit are shown in Figure 3. They are high energy tubular battery, PTFE membrane, steam boiler, membrane housing and solar PV cell array unit.

Performance testing found that at brine feed temperature of 95°C, while maintaining the other side of the membrane at 32°C, water flux of 0.5 l/m^2 h was achieved for laboratory-scale membrane distillation and the measured TDS was 8 ppm; salt rejections greater than 97.5% were typical.

$$\text{Salt passage} = \frac{\text{TDS of permeate}}{\text{TDS of feed}}.$$

$$= \frac{8}{323 \times 100} = 2.5\%.$$

$$\text{Salt rejection} = (1 - \text{salt passage})$$
$$= (1 - 0.025) = 97.5\%.$$

The thermal efficiency (η_T) was calculated using the following equation[19]

$$\eta_T = JH_vA/m_FC_p\ (T_F \text{ inlet} - T_F \text{ outlet}),$$

where J is the permeate flux, H_v the latent heat of vaporization, A the area of membrane module, m_F the mass feed flow rate, C_p the specific heat of feed and T_F is the temperature of the feed.

For solar PV-driven MD, experimental thermal efficiency = $0.502 \times 2270 \times 5.6/40 \times 3.54 \times 10^{-2} \times 4.21 = 95\%$.

For conventional MD, experimental thermal efficiency = $0.388 \times 2270 \times 5.6/40 \times 3.54 \times 10^{-2} \times 4.21 = 83\%$.

The data obtained from design specifications were used to calculate the energy efficiency.

Power conversion efficiency of PV cells was calculated using the expression[12]

$$\text{Photovoltaic energy efficiency } \eta_e = 5.75 \times 17.4/1000 \times 0.3 = 33\%.$$

Results and discussion

Using PV cells in membrane processes for desalination could be an interesting alternative in remote areas. A commercial PV technology coupled with RO system is currently available[20]. Energy requirement for solar PV coupled with RO for brackish water desalination is approximately 1.3 kW/h m^3. The energetic system consists of a PV field of 0.45 kW peak for 1 m^3/day of plant capacity which is functional in Thar desert, India[21]. However, solar PV integrated to thermally driven MD is still at research level.

In solar power MD, data are obtained as a collection of volume of product distillate as a function of time for solar mode (Table 2). It can be inferred from Figure 4, that the flux fluctuates with time and then decreases; this may be due to temperature polarization effect and low vapour pressure due to loss of convective heat transfer across the membranes. This effect is more pronounced for MD without solar power mode where there is a steady decrease in the flux (Figure 5). It can be seen from Figure 6 that the production of distillate increases with time for the solar mode. However, the amount of water collected for the conventional process is less for the same calculated time interval compared to the solar PV-driven MD (Figure 7). Table 3 shows data obtained as a collection of volume of product distillate with function of time for conventional mode.

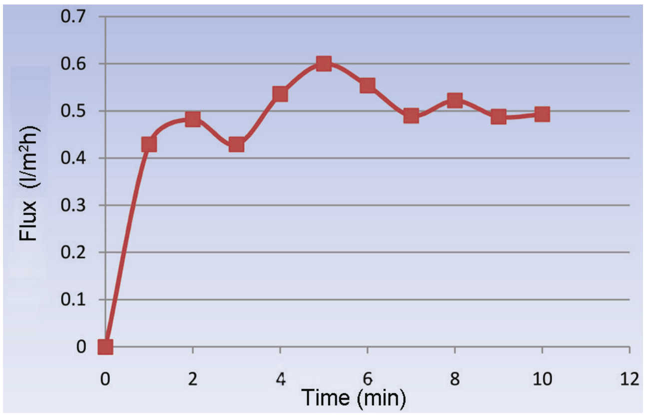

Figure 4. Time versus permeate flux – solar mode.

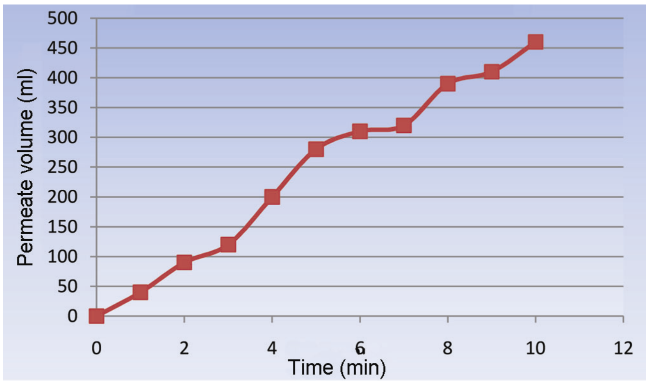

Figure 5. Time versus permeate volume – solar mode.

Table 2. Desalination of tap water by solar PV membrane distillation

Time (min)	Permeate volume (ml)	Permeate flux (l/m^2 h)
0–1	40	0.429
0–2	90	0.482
0–3	120	0.429
0–4	200	0.536
0–5	280	0.6
0–6	310	0.554
0–7	320	0.49
0–8	390	0.522
0–9	410	0.488
0–10	460	0.493

Table 3. Desalination of tap water by conventional membrane distillation

Time (min)	Permeate volume (ml)	Permeate flux (l/m^2 h)
0–1	50	0.536
0–2	90	0.482
0–3	125	0.446
0–4	140	0.375
0–5	160	0.343
0–6	210	0.375
0–7	220	0.337
0–8	250	0.335
0–9	270	0.321
0–10	310	0.332

Table 4. Water quality analysis by geochemical laboratory

Particulars	Tap water	RO water	Membrane distillation water
Electrical conductivity (μs@25)	600	15	11
pH	7.5	8	7.4
Calcium (mg/l)	60	2	2
Magnesium (mg/l	28	1	0
Sodium (mg/l)	15	0	0
Potassium (mg/l)	0	0	0
Bicarbonate (mg/l)	305	6	6
Carbonate (mg/l)	0	0	0
Sulphate (mg/l)	22	1	1
Chloride (mg/l)	43	1	1
Nitrate (mg/l)	9	1	1
Fluoride (mg/l)	0.41	0	0
Total dissolved solids (mg/l)	323	9	8
Total hardness as $CaCO_3$ (mg/l)	230	7.5	5.5
Total alkalinity as $CaCO_3$ (mg/l)	250	5	5

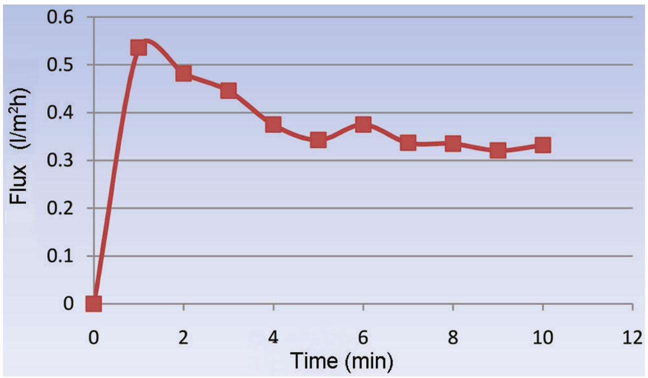

Figure 6. Time versus permeate flux – conventional mode.

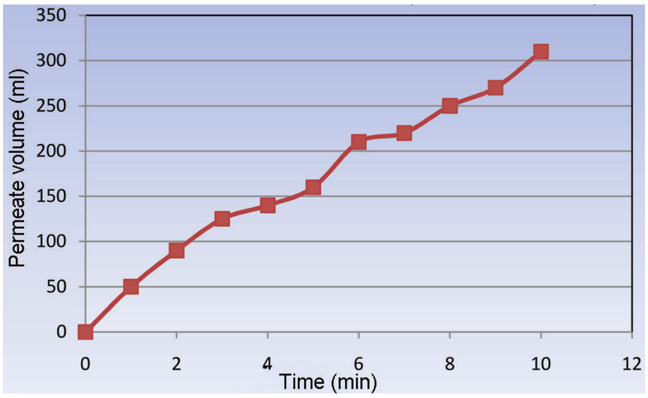

Figure 7. Time versus permeate volume – conventional mode.

For the solar PV-driven MD, the product distillate achieved was 63 l/day, the permeate flux was 0.502 l/m^2 h, specific thermal heat consumption 1030 kJ/h and power consumption was 0.285 kW. It is a low power consuming desalination technology because it utilizes low waste heat energy and requires less auxillary equipments, unlike RO. The flux value and heat efficiency for solar power MD are in good agreement with those reported in the literature; the experimental efficiency was found to be 95%.

Using the conventional mode, the product distillate achieved was 44 l/day, permeate flux was 0.388 l/m^2 h, specific thermal heat consumption was 728 kJ/h and power consumption was 0.202 kW. The experimental efficiency was found to be 83%, which is less compared to the MD operating in solar mode.

Thus from the calculation of effectiveness of the solar PV-driven MD in desalination, it can be inferred that solar-powered thermal efficiency is 95% compared to the 83% efficiency of conventional mode. Electric power consumption for solar mode was measured as 1.3 kWh and for MD conventional mode it was 2.5 kWh. The observed decrease of the permeate flux and thermal efficiency is probably also influenced by a significant decrease in convective heat transfer coefficient across the membrane for conventional thermal MD.

Chemical analysis of water

Samples obtained were sent for water quality analysis to a government authorized geochemical laboratory. Table 4 provides the results of the analysis.

From Table 4, it can be inferred that salts like sodium and potassium, and fluoride which cause health hazards are completely removed by both RO and MD methods making the water fit for drinking. The hardness of water is high for RO compared to MD, proving that thermal MD is better for the production of high-quality distilled water.

Conclusion

It can be concluded from the results of the present study that solar PV-driven MD is a viable technology for low-scale processes in remote areas where grid connection is limited. It can be installed as a stand-alone mode. However, maintenance of the instrument is necessary for preventing fouling of membrane. As the membrane used in this process is hydrophobic, the probability of fouling is less compared to RO membrane and thin-film composite membrane.

This article highlights the feasibility of utilizing solar energy in arid and semi-arid regions with shortage of drinking water and can be a one-time investment where provision of energy is expensive. It would be beneficial if renewable energy is well utilized in small communities with contaminated water resources and lack of electricity. Future work can focus on the production cost of water and economic analysis of this system.

1. Pangarkar, B. L., Sane, M. G. and Guddad, M., Reverse osmosis and membrane distillation for desalination of groundwater: a review. *ISRN Mater. Sci.*, vol. 2011; doi:10.5402/2011/523124.
2. Busch, M., Chu, R., Kolbe, U., Meng, Q. and Li, S., Ultrafiltration pretreatment to reverse osmosis for seawater desalination – three years field experience in the Wangtan Datang power plant. *Desalination Water Treatment*, 2009, **10**, 1–20.
3. Kalogirou, S. A., Solar thermal collectors and applications. *Prog. Energy Combust. Sci.*, 2004, **30**, 231–295.
4. Pachanri, R. K., *From Sunlight to Electricity – A Practical Handbook on Solar Photovoltaic Application*, Copyright by TERI Press, New Delhi, 2008, p. 43.
5. Nikhil, P. G., A look at peak sunshine hours used in solar system design, renewable energy. *Akshay Urja*, 2014, **7**(4).
6. Wright, N. C., Amos, G. and Winter, V., Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India. *Desalination*, 2014, **352**, 82.
7. Al-Karaghouli, A., Renne, D., Kazmerski, L. L., Technical economic assessment of photovoltaic-driven desalination systems. *Renewable Energy*, 2010, **35**, 323.
8. Ranjan, K. R. and Kaushik, S. C., Economic feasibility evaluation of solar distillation systems based on the equivalent cost of environmental degradation and high-grade energy savings. *Int. J. Low-Carbon Technol.*, 19 July 2013; doi:10.1093/ijlct/ctt048.
9. Ali Abbas, M. and Al-Karaghouli (Al-Qaraghuli), Renewable energy applications in water desalination. In 56th Annual New Mexico Water Conference, 2011, pp. 79–87.
10. Al-Obaidania, S., Curcio, E., Macedonio, F., Di Profio, G., Al-Hinai, H. and Drioli, E., Potential of membrane distillation in sea water desalination: thermal efficiency, sensitivity study and cost estimation. *J. Membr. Sci.*, 2008, **323**, 85–98.
11. Cuce, P. M. and Cuce, E., A novel model of photovoltaic modules for parameter estimation and thermodynamic assessment. *Int. J. Low-Carbon Technol.*, 2012, **7**, 159–165.
12. Joshi, A. S., Dincer, I. and Reddy, B. V., Analysis of energy and exergy efficiencies for hybrid PV/T systems. *Int. J. Low-Carbon Technol.*, 2011, **6**, 64–69.
13. Gabsi, S., Frikha, N. and Chaouachi, B., Performance of a solar vacuum membrane distillation pilot plant for seawater desalination in Mahares, Tunisia. *Int. J. Water Resour. Arid Environ.*, 2013, **2**(4), 213–217.
14. Chang, H., Lyu, S.-G., Tsai, C.-M., Chen, Y.-H., Cheng, T.-W. and Chou, Y.-H., Experimental and simulation study of a solar thermal driven membrane distillation desalination process. *Desalination*, 2012, **286**, 400–411.
15. http://www.psa.es/webeng/projects/medesol/index.html
16. Hanemaaijer, J. H., van Medevoort, J., Jansen, A. E., Dotremont, C. and van Sonsbeek, E., Memstill membrane distillation – a future desalination. *Desalination*, 2006, **199**, 175.
17. Younas, O., Banat, F. and Didarul Islam, Md., Performance assessment of a multi-stage solar still coupled with Fresnel lens for water desalination. TEPE Volume 2013, Issue 4, pp. 164–170.
18. *Membrane Systems for Waste Water Treatment*, Water Environment Federation, McGraw-Hill, 2006, p. 9.
19. Gryta, M., Effectiveness of water desalination by membrane distillation process. *Membranes*, 2012, **2**, 415–429.
20. Garcia-Rodriguez, L., Sea water desalination driven by renewable energies: a review. *Desalination*, 2002, **143**, 103–l13.
21. *Desalination Guide Using Renewable Energies*, European Commission, Brussels, 1998.

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