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Research Paper

A Novel Photovoltaic Powered Reverse Osmosis with Improved Productivity of Reverse Osmosis and Photovoltaic Panel

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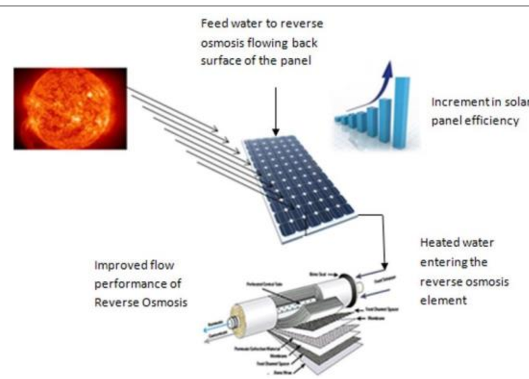
HIGHLIGHTS

- PV cooling from the back.
- PV-RO productivity increased.
- PV efficiency increased.

GRAPHICAL ABSTRACT



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ABSTRACT

With the increasing installed capacity of desalination, the greenhouse gas emission for generating the required energy to power the desalination plants is also becoming the focus of attention in the world community. Domestic reverse osmosis membranes have been very successful technology especially in the developing world to provide safe drinking water. The novel concept of photovoltaic powered RO with thermal energy recovery from the photovoltaic panel has been presented. The problem with photovoltaic technology is its sensitivity to temperature. The efficiency of the photovoltaic panel declines at higher temperature. The present paper demonstrates that the thermal energy can be captured by flowing water to maintain the temperature of the photovoltaic panel at the same time the captured thermal energy can be harnessed for useful purposes. The direct utilization of high temperature water is the most attractive option from an overall energy efficiency point of view. The present paper demonstrates that the captured thermal energy from the PV panel can be successfully utilized when cooling water is feed water to reverse osmosis. The higher temperature feed water to reverse osmosis decreased the energy consumption of reverse osmosis up to 28% and increased the total product water output by 20% with up to a 10oC rise in feed water temperature during the day. The paper also explains the sensitivity of membrane transport with temperature. The present paper opens the possibility of system development and poses the win-win combination of higher photovoltaic panel efficiency with the utilization of captured thermal energy which in turn curbs greenhouse gas emissions.

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1. Introduction

Solar powered reverse osmosis is the most widely practiced desalination technology among all renewable energy powered desalinations. Photovoltaic-powered reverse osmosis (PV/RO) is a convenient method for desalinating water, especially for many small, remote, off-grid communities. Many researchers installed the experimental facility to power reverse osmosis plants with solar photovoltaic technology. However, the cost of producing fresh water by such a process is rather expensive- and is reported to be 6.52 $/cubic meters of fresh water over the 20- year life time of the equipment [13].

A prototype photovoltaic-powered reverse-osmosis system is designed to operate from seawater, and a Clark pump brine-stream energy recovery mechanism is coupled with a variable recovery ratio technique to achieve a specific energy consumption of less than 4 kWh/m^3 over a wide range of operations [10].

The solar thermal-powered reverse osmosis desalination system was coupled to a solar power cycle based on a Rankine cycle [1]. A solar-powered trans-critical CO_2 (carbon dioxide) power cycle for reverse osmosis desalination has been studied [5]. A hybrid wind/solar powered reverse osmosis desalination system has been modelled and simulated [3]. A solar thermal and photovoltaic-powered reverse osmosis (RO) desalination plant has been constructed and optimized for brackish water desalination [6]. Desalination of brackish water as a viable option to cope with water scarcity and to overcome water deficiency has been studied in Jordan [4]. A prototype photovoltaic-powered reverse-osmosis system has been constructed at CREST, Loughborough, UK. The rate of production of fresh water varies throughout the day according to the available solar power, and thus the unit operated without batteries has been demonstrated [10]. The novel solar powered direct osmosis desalination process has been demonstrated [11]. The life cycle of Greenhouse Gas (GHG) emissions of a Seawater Reverse Osmosis (SWRO) desalination plant has been assessed and it was found that GHG emissions reduction of about 90% can be achieved by opting for renewable energy [7]. Front cooling of the PV panel with water has been attempted and the experimental data of panel temperature closely matched computational fluid dynamics simulation simulated data [15]. An attempt has also been made to make the membrane more temperature sensitive to get a higher increase in flow with increase in temperature [16].

Thus, many researchers attempted to study solar powered reverse osmosis and its application for seawater and brackish water desalination. However, the domestic reverse osmosis plant powered by solar photovoltaic panel clubbed with feed water heating and solar panel cooling is the unique combination to achieve high energy efficiency as shown in the present paper.

Life cycle greenhouse gas emission of a coal based thermal power plant is 820 g Carbon dioxide/ KWH whereas the same for solar PV is 48 g Carbon dioxide/KWH [9]. Renewable energy powered desalination seems very attractive on prima facie; however, the high capital cost of renewable energy generation and lower reliability in terms of consistency are the major impediments in its implementation. To make the renewable energy powered desalination attractive, the energy requirement for desalination should be minimized and the options of using low grade energy, i.e. waste heat can be explored.

The feed water temperature can be increased by any low grade heat source. Increased temperature of feed water improves the product water flow rate to a substantial extent with slight decline membrane selectivity; which avoids the re-mineralization of product water.

The specific energy consumption can be reduced by the following methods from the first principle [8].

1. Increasing number of stages
2. Using energy recovery device
3. Increasing $\Upsilon = A_{total} L_p \Delta\pi_o / Q_f$ (1)

$L_p = CLP \bullet Exp(-Ea^{LP}/RT)$ [2] (2)

where L_p is the hydraulic permeability; CLP is Constant; $\Delta\pi_o$ is the difference in osmotic pressure on either side of the membrane; A_{total} is total membrane area; Q_f is the volumetric flow rate of feed; Ea^{LP} is the activation energy represents the per mole difference in enthalpy of a molecule which is necessary to overcome the transport barriers during its passage across the membrane; and *T* is the temperature of feed water.

Substituting (2) in (1):

$$\Upsilon = A_{total}\, CLp \bullet Exp(-Ea^{LP}/RT)\, \Delta\pi_o / Q_f \quad (3)$$

Thus, with an increase in temperature, ϒ increases. Therefore, *T* has to be maximized for maximizing ϒ. Hydraulic permeability increases at higher temperature which in turn results in improved ϒ. Similarly, increasing the number of stages and using energy recovery devices will also reduce the specific energy consumption for reverse osmosis.

The present paper demonstrates that the reverse osmosis feed water temperature can be increased by low grade heat available from the solar photovoltaic panel thereby cooling the photovoltaic panel. The solar photovoltaic panel efficiency improves and the captured thermal energy can be utilized indirectly to decrease the energy consumption of reverse osmosis.

2. Experimental1

2.1. Materials

70 Watt Solar photovoltaic panels 6 nos. (2 sets of 3 connected in series), frame structure, Domestic RO pump, Cartridge filter, Domestic RO membrane with membrane area of 0.55 square meter. (One element), filter housing for RO membrane and cartridge filter, tanks.

2.2. Method

Three nos. of photovoltaic panels (70 Watt peak output each) are connected in series as shown in Figure 1. Two sets of a similar kind are created. In one of the sets, the water chambers have been provided at the back side of the panel to flow water of the total dissolved solids concentration 500 mg/l. The initial temperature of water is 35 ºC and is flowing in the chamber by gravity from the overhead tank and the water at the outlet is collected in the common header and passed through the cartridge filter by gravity. The filtered water is pumped to the RO membrane by a domestic RO pump. The domestic RO pump's voltage rating is 48 volt DC that is directly connected to the photovoltaic panel. The pump works as a resistance to collect power data generated by the photovoltaic panel. The flow of the pump with changes in voltage was monitored. The operating pressure of RO was 50 psig and the pressure drop during the operation was monitored. Energy losses from the photovoltaic panel to ambient environment have been ignored.

Fig. 1. (a) Photovoltaic panels kept at 20º inclination from horizontal; (b) RO plant associated with PV panel.

The pump is connected by two sets of PV panel systems with a switch to either connect to the panel or disconnect from the other. The power data were monitored every hour for both sets, i.e. with and without water cooling at the back surface by a clamp-on power meter. The permeate water flow rate and solute rejection of the domestic RO membrane element were monitored with time (see Figure 2).

Thermal images of the PV panel have also been captured by a Testo Thermal imager to identify the localized and average temperature of the photovoltaic panel.

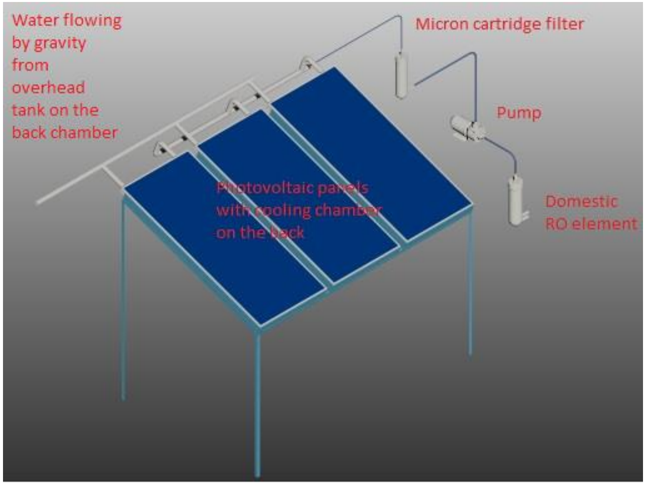

Fig. 2. Schematic Experimental Set-up with dimensions.

3. Results and discussions

The photovoltaic panel absorbs part of the solar radiations and converts them into electricity. A majority of this radiation heats up the panel - as a result; the electrical conversion efficiency of the photovoltaic panel decreases. Thus, the beneficial effects of photovoltaic panel cooling can be divided into two:

1. Improvement in Reverse Osmosis membrane performance
2. Improvement in photovoltaic panel performance.

3.1. Improvement in Reverse Osmosis membrane performance

The water captured thermal energy while cooling the photovoltaic panel. The heated water was passed to the domestic RO membrane element through a cartridge filter to remove the suspended solids if any. The rise in permeate water flow was observed with time as the feed water temperature increased with time. Table 1 and Figure 3 demonstrates that the permeate water flow rate increased by 38.82% when the water temperature increased from 35 ºC to 45 ºC. Table 1 also demonstrates the captured thermal energy with time.

Table 1
Capture of thermal energy by flowing water on the back side of the PV panel.

Sr. No.	Time (Hrs)	Flow of domestic RO membrane element ml/minute	Permeate Total dissolved solids (mg/l)	Water temperature (ºC)	Captured thermal energy (watt)	Pressure drop from inlet to outlet psig
1.	1000	85	40	35	0	2
2.	1100	90	41	37	251.22	3
3.	1200	110	42	43	1004.88	3
4.	1300	114	42	44	1130.49	2
5.	1400	118	43	45	1256.1	3
6.	1500	105	41	41	753.66	3
7.	1600	98	40	39	502.44	2
8.	1700	92	40	38	376.83	2

Table 2
Water temperature with flow rate and power produced.

Time of day (Hrs)	Water temperature (ºC)	Water flow rate (ml/minute)	Power Produced by PV panel (Watt)	Recovery of water (%)
1000	35	1440	185	5.9
1100	37	1600	202	5.62
1200	43	1660	210	6.62
1300	44	1740	220	6.55
1400	45	1700	200	6.94
1500	41	1660	175	6.32
1600	39	1600	160	6.12
1700	38	1520	125	6.05

Table 2 indicates that as the day progresses, the water temperature increases, and simultaneously power produced by the PV panel also increases. With increasing DC voltage, water flow rate of the pump also increased, thus, water flow rate also increased during the day and decreased with a decrease in temperature.

Figure 3 shows that the permeate water flow rate of the domestic RO membrane element increases from 85 ml/minute to 118 ml/minute as the temperature of feed water increases from 35 ºC to 45 ºC. The error bars are also shown and the flow and temperature results are within the error band of 1.5%. The total outputs permeate water quantity increases by 20% over a 7 hour period from 1000 hrs to 1700 hrs. The curve fitting shows that both flow and temperature of feed water follows a parabolic pathway as it increases and then decreases during the day. The R^2 value in the case of flow performance is ca. 0.87, which is a good fit and in the case of temperature it is ca. 0.85. The deviation of R^2 value from 1 indicates not only the experimental error but many other unpredictable factors such as wind speed change in solar radiation intensity, etc.

3.2. Improvement in photovoltaic panel performance

The power produced by photovoltaic panels with and without cooling has been recorded with time. The water used for cooling is feed water to domestic RO membrane element. Figure 4 demonstrates that the power produced by the photovoltaic panel with cooling is higher as compared to the power produced without cooling at all times. Error bars are shown and the power produced with and without cooling is within an error band of 2%. About 8-10% average increments in power production have been noted. Thus, the improvement in photovoltaic panel efficiency has been recorded.

Figure 5 shows that the temperature of the photovoltaic panel can be controlled by cooling from the back side of the panel. The panel without cooling was 59.1 ºC at 12:00 noon whereas the temperature of the panel with cooling was 34.3 ºC at the same time. Thus, the difference in panel temperature with and without cooling was about 25 ºC. However, at 1400 hrs the difference in the panel temperature with and without cooling was only ca. 12 ºC. This is because of rise in feed water temperature.

The captured thermal energy has been successfully utilized to decrease the energy consumption of reverse osmosis. Table 1 indicates that the flow increases from 85 ml/minute to 118 ml/minute when the temperature rises from 35 ºC to 45 ºC. This indicates that the domestic RO pump of 12 watt rating has to run for 196 hours to produce 1 cubic meter of water with 85 ml/minute flow rate whereas the same pump has to run for 141 hours to produce 1 cubic meter of water with 118 ml/minute flow rate. Thus, the energy consumption to produce a cubic meter of fresh water by domestic RO decreases from 2.352 Kilowatt-hour to 1.694 Kilowatt-hour- that indicates ca. 28% decline in energy consumption.

The dynamic viscosity of water decreases from 0.7194 mPa-s to 0.5960 mPa-s when its temperature increases from 35 ºC to 45 ºC [12]. The decline in viscosity indicates that the resistance to flow decreases; which in turn, results in increased flow performance of the membrane.

Thus, the paper demonstrates the feasibility of deriving the energy advantage from the photovoltaic powered domestic RO systems by feed water heating. The feed water was used as available to address the actual problem. It is understandable that the photovoltaic panel temperature can be more effectively controlled if the feed water is at a lower temperature and also the differential feed water temperature will increase in that case.

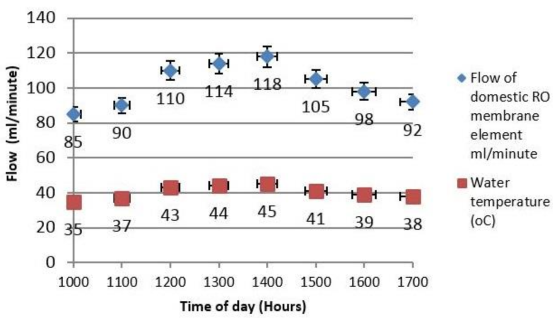

Fig. 3. Flow performance of domestic RO membrane with temperature.

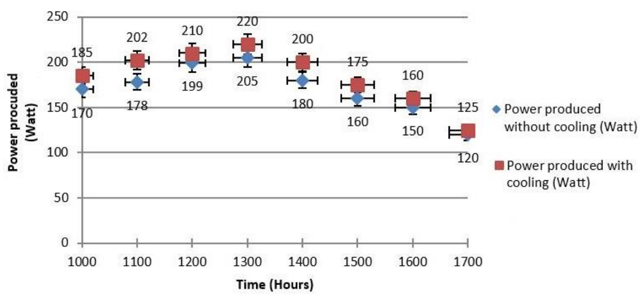

Fig. 4. Power produced by PV panel with and without cooling.

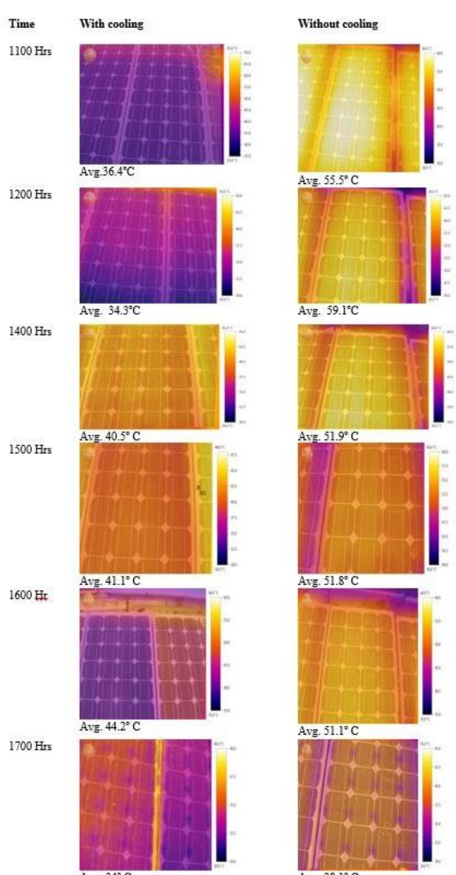

Fig. 5. Thermal images of PV panel with and without cooling at different time during the day.

4. Conclusion

The temperature of the photovoltaic panel was controlled by flowing water at the back side of the panel and thermal energy was recovered from the solar photovoltaic panel and also utilized for useful application. The following conclusions were derived:

1. Domestic reverse osmosis RO membrane permeate flow rate increased with an increase in temperature of water from 85 ml/minute at 35 ºC to 118 ml/minute at 45 ºC. This indicates that the tapped thermal energy in feed water to reverse osmosis improves the productivity of the reverse osmosis membrane by decreasing feed water viscosity.
2. The cooling water can control the temperature of the PV panel. The difference in the average temperature of the PV panel with cooling and without cooling is at its highest at 12:00 noon where the temperature of the PV panel was 34.3 ºC with cooling and 59.1 ºC without cooling. The power produced by the PV panel was increased with cooling on the back side as the temperature of the PV panel was kept lower.
3. Total water output over a 7 hour period was increased by 20% by heating feed water for solar photovoltaic panel cooling.
4. It has been demonstrated that the specific energy consumption of reverse osmosis decreases by ca. 28% when the feed water temperature increases by 10 ºC.

Thus, the proposed approach demonstrates the win-win combination of improved photovoltaic panel efficiency and thermal energy recovery. Thus, it opens the opportunity for further work in developing systems with higher energy efficiency to curb greenhouse gas emissions.

Nomenclature

A_{total}: Total membrane surface area
C_{LP} = Constant
Ea^{LP} = Activation energy represents the per mole difference in enthalpy of a molecule which is necessary to overcome the transport barriers during its passage across the membrane
KWH: Kilo watt hour
L_p: Hydraulic permeability
mPa-s: Milli pascal second
PV: Photovoltaic
RO: Reverse Osmosis
T = Temperature
W_p: Watt peak
ϒ: Co-efficient representative of permeability

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