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Development of Ultra-Low Energy Reverse Osmosis Process for Solar Photovoltaic

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Abstract: In order to improve the performance of the PV panel and recover energy, the current research discusses controlling the temperature of solar PV panels by direct contact heat exchange with flowing feed water to reverse osmosis from the top of the panel. The flow performance of the membrane was enhanced via reverse osmosis at a higher temperature. Additionally, the flow performance was enhanced by the controlled sodium hypochlorite treatment, which changed the membrane's shape and increased its hydrophilicity, as shown by the fall in contact angle from 48.050 to 26.220. Thus, a two-pronged approach to improving the electrical performance of PV panels and enhancing RO permeate flow involved regulating the temperature of the panels through heat transfer and modifying the membrane shape to be more hydrophilic. Reverse osmosis's overall energy usage has thus been lowered by around 40%. This innovative method creates opportunities to drastically lower the total energy uses of brackish water reverse osmosis systems.
Keywords- PV Panel, Heat Exchanger, Reverse Osmosis, membrane morphology.

1. INTRODUCTION

Through the technique of "reverse osmosis," which involves pushing water through semi-permeable membranes, salty ocean water may be converted to freshwater. Reverse osmosis membranes are thin film composites consisting of nonwoven polyester, polysulfone, and a polyamide barrier layer, which allows them to remove not only suspended particles but also salts, germs, and viruses. This allows the procedure to be carried out in order to eliminate suspended solids. Water flow is mostly driven by pressure; hence energy must be used by the membrane process to create water. This is so because water movement is propelled by pressure. This means that in order for facilities that employ the reverse osmosis process to function properly, they need a reliable source of electricity. Reverse osmosis plants driven by the sun present an interesting option for building plants in isolated parts of developing nations with erratic access to electricity sources, but situated in areas with strong solar radiation, like the tropics. Solar-powered reverse osmosis has been considered one of the most promising technologies for reducing greenhouse gas emissions and for standalone systems for reclaiming land in rural and isolated areas. Over the last decade, reverse osmosis has developed into a reliable technology that has been successfully applied in several areas worldwide. Most of this progress took place in the US. However, the amount of energy required to create water remains a significant source of worry. For every cubic meter of feed water, water treatment plants require around 3-5 kWh of energy in order to produce freshwater from saltwater and brackish water, respectively. The amount of energy required might be greatly impacted by the feed water's total dissolved solids content. Aburub, A., et al. (2017) [1] "presented the performance of water-heated, cross-flow humidification dehumidification (HDH) desalination system with brine recirculation designed, constructed, and operated in a controlled environment. They introduced HDH devices that were simple to construct, simple to maintain, and ideal for distant places with little technical expertise. The impact of mass ratio (MR) on GOR, RR, humidifier, and dehumidifier efficacy was studied. The system was tested at 60-75 oC hot water temperatures and 4- 18 L/min hot water flow rates. The developed system can produce 92 liters of distillate water per day, has a GOR of 1.3, and the component efficacy ranges from 92–97 percent for a dehumidifier and 53–79 percent for a humidifier". Ahmad, N., et al. (2015) [2] "presented analytical modeling and simulation with experimental verification of photovoltaic system driving reverse osmosis water desalination. In a photovoltaic system, the influence of fixed and tracking PV panels on collected insolation and PV power was studied. The RO division created a full membrane model that predicts feed water pressure and permeates flow rate. The proposed PV and RO models were verified by experimental data singly and together (combined PVRO). Using this verified model, the influence of PV panel slope and azimuth angle on permeate flow rate was explored yearround. The clean water flow rate increments for annual tilt, monthly tilt, and single and double-axis tracking PV panels are determined. A year-round ideal tilt angle of PV panels due south was close to 0.913 times Dhahran's latitude. Annual permeate gain with annual optimum tilt and monthly optimal tilt of PV panel installation vs to flat panel installation was 10% and 19%. Using single and dual-axis tracking systems, the PV orientation (tilt angle and azimuth angle) may be adjusted. The annual permeate gain of single and double-axis continuous tracking PV panels is 43% and 62%". Ahmed, F. E., et al. (2019) [4] "discussed the most recent developments in photovoltaic powered reverse osmosis (PV-RO), solar thermal powered reverse osmosis (ST-RO) with respect to membrane materials, process configuration, energy recovery devices, and energy storage. Globally, desalination capacity has increased significantly to meet rising water demand. The focus has switched to employing renewable energy sources to reduce the carbon impact of high-energy desalination procedures. Sun-powered desalination offers a sustainable answer to water shortages in locations with abundant solar irradiation. The compatibility of any desalination process with solar technology is determined by the kind of energy required and its availability. Because photovoltaic and solar thermal solar energy technologies are rapidly developing, there is considerable interest in linking solar energy with desalination to improve energy efficiency. Also covered were recent developments in sun-powered membrane distillation (MD) and still solar materials. The future forecast involves solarpowered forward osmosis and evaporation. The technology and energy usage of solar-powered desalination devices has been studied". Alghoul, M. A., et al. (2016) [5] "quantify the effect of climatic-design-operation conditions on the performance and durability of a PV-BWRO desalination system. Small-scale brackish water reverse osmosis (BWRO) desalination facilities are less profitable than large-scale ones. Integrating renewable energy systems with small-scale units might hypothetically help their commercialization. In reality, RO units are modular, allowing them to adapt to renewable energy sources. Small-scale PV-RO desalination systems might be useful in distant places where BW is more widespread. A 6-month small-scale unit is developed, built, and tested. Only a 2 kWp PV system with five membranes, a feed TDS of 2000 mg/l, and a permeate TDS of 50 mg/l were allowed. Data on solar radiation and temperature were studied to establish their impact on the unit's present and future activities. A two-stage design was shown to be optimal for 600 W RO load, membrane type, and design configuration. The PV system was able to provide the load while the RO unit maintained steady permeate flow and salinity. Using the PV-BWRO system for 10 hours would create 5.1 m3 of fresh water at 1.1 kWh/m3. There are several hours of high temperatures during PV module operation (over 45°C) and battery room conditions (above 35°C), both of which might significantly affect power output and battery autonomy. Optimum thermal management of PV module and battery bank room conditions is vital in maintaining optimal operating temperatures". Ali, E. S., et al. (2017) [7] "investigated the effect of reverse osmosis brine recycling employing adsorption desalination on overall system desalinated water recovery. The input, pretreatment, and brine disposal costs of reverse osmosis seawater desalination systems account for around 25% of the overall cost. Adsorption desalination creates high-quality drinkable water and a cooling effect. The brine from the RO system feeds the adsorption desalination system. Low-temperature heat sources like solar energy power it. MATLAB triggered the adsorption desalination system. The suggested combination approach improves recovery while decreasing permeate salinity. Aside from improved system performance, a cooling effect is created, that may be used for cooling". Ali, I. B., et al. (2014) [9] "investigated systemic modeling of a small-scale Brackish Water Reverse Osmosis (BWRO) desalination unit. This device was powered by a photovoltaic-wind hybrid system with no batteries. The RO desalination process involves mechanical, hydraulic, chemical, and thermal fields. Thus, this study proposes an interdisciplinary strategy. The bond graph is a well-known dynamic modeling tool for such a multi-physical system. A BWRO test bench is characterized experimentally to evaluate the developed bond graph model of the examined desalination process. The simulation findings show considerable results when compared to the experimental results".

2. RESEARCH GAP

There has always been worry about reverse osmosis's energy usage. Energy usage has been continuously decreasing since the development of RO technology. Though, as previously said, there is room to reduce the energy consumption because it is now higher than the thermodynamic minimum energy consumption. It has been determined from the first principle that the following techniques can lower the specific energy required for reverse osmosis. [1].

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

Hydraulic permeability (Lp) can be found by the equation below [2].

$$L_p = C_{LP} \cdot \exp(-E_{aLP}/RT) \quad \text{(Eq.2)}$$

CLP = Constant

EaLP = 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

T = Temperature Substituting (2) in (1)

$$\Upsilon = A_{total}\, C_{LP} \cdot \exp(-E_{aLP}/RT)\, \Delta\pi_o / Q_f \quad \text{(Eq.3)}$$

Therefore, temperature has to be maximized for maximizing ϒ. Increase in hydraulic permeability at higher temperature results in increased ϒ.

The other effect on increased feed water temperature is increase in osmotic pressure.

Osmotic pressure can be found by $\prod = C * R * T$ (Eq. 4)

where; $\prod$ = osmotic pressure in atm C = Concentration in mol/l

R = Constant in lt*atm/mol*K T = Temperature in OK

Therefore, for a given feed water content, an increase of 3.27% in osmotic pressure will occur with a temperature rise of 10,000 Kelvin. The impact mentioned above will be offset by a rise in osmotic pressure. Nonetheless, the advantage of improved flow performance due to feed water viscosity drop outweighs the marginal rise in osmotic pressure. When water's temperature rises from 35 to 45 degrees Celsius, its dynamic viscosity drops from 0.7194 mPa-s to 0.5960 mPa-s, or 17.15% [3]. The drop in viscosity signifies a reduction in flow resistance, leading to an improvement in the membrane's flow performance. This explains why a rise in temperature will result in an overall rise in the flow of water.

Reverse osmosis's specific energy consumption can be decreased by adding more stages, using an energy recovery device, or both. Low-grade thermal energy from feed water heating as it passes over the solar photovoltaic panel, however, can affect the temperature of the feed water, leading to an increase in hydraulic permeability of the membrane and an increase in temperature.

Indirect solar thermal energy capture is made possible by the use of heated water in reverse osmosis to lower the process' energy consumption and heat transfer from solar panels to cold water on their upper surface. Furthermore, the reverse osmosis process uses less energy when the shape of the membrane is altered to enhance its permeability. Consequently, the work shows for the first time that seemingly unrelated components—thermal energy recovery from solar PV panels from both the top and bottom and improved membrane morphology for increased permeability—can be coupled to produce synergistic results in brackish water reverse osmosis performance.

3. EXPERIMENTATION: PHOTOVOLTAIC PANEL COOLING FROM THE BACK SIDE

3.1 Materials

70-Watt photovoltaic solar panels Six in number (two sets of three linked in series), a frame construction, a domestic RO membrane with a 0.55 square meter membrane area (one element), a cartridge filter, a domestic RO pump, filter housing for the RO membrane and tanks.

3.2 Method

Figure 1 illustrates the series connection of three solar panels, each with an output of 70 Wp. There are produced two sets of the same sort. Water with a 500 mg/l total dissolved solids content can pass through chambers located on the panel's back in one of the sets. Water enters the chamber by gravity from an above tank at a temperature of 35 °C. At the outflow, water is gathered in a common header and gravity-carries it through a cartridge filter. A residential RO pump delivers the filtered water to the RO membrane. 48-volt DC is the voltage rating for the household RO pump, which is directly linked to the solar panel. It was observed how the pump's flow changed when the voltage changed. The RO was working at 50 psi, and the pressure decrease that occurred while it was functioning was tracked. Photovoltaic panel energy losses to the surrounding environment have not been taken into consideration.

Two sets of PV panel systems, each having a switch to connect to one panel and disengage from the other, are used to connect the pump. Every hour, a clamp-on power meter was used to track the power data for both sets—one with and one without water cooling at the rear surface. Over time, the home RO membrane element's solute rejection and permeate water flow rate were observed. In order to determine the PV panel's average and localized temperature, Testo Thermal Imager has also taken thermal pictures of the panel.

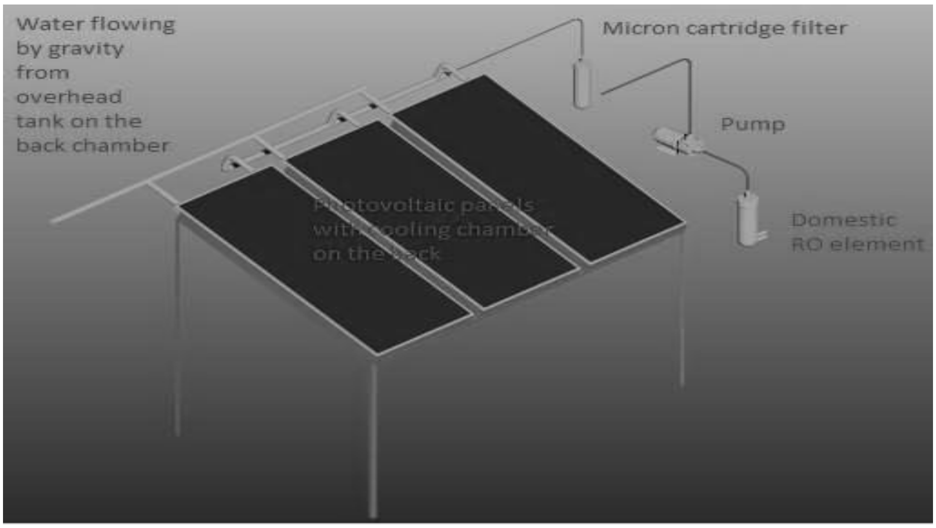


Figure 1. Schematic Experimental Set-up

4. RESULTS AND DISCUSSIONS

Photovoltaic panel absorbs the part of solar radiations and convert them into electricity. Majority of this radiation heat up the panel as a result; the electrical conversion efficiency of 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.

4.1 Improvement in Reverse Osmosis Membrane Performance

As the water cooled the solar panel, it absorbed thermal energy. To eliminate any suspended particles, if any, the hot water was sent via a cartridge filter to a household RO membrane element. As the temperature of the feed water rose over time, a rise in permeate water flow was seen. Table 1 shows that when the water temperature rose from 35 0C to 45 0C, the permeate water flow rate increased by 38.82%. Additionally, Table 1 shows the thermal energy that is gathered throughout 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.	10:00	85	40	35	0	2
2.	11:00	90	41	37	251.22	3
3.	12:00	110	42	43	1004.88	3
4.	13:00	114	42	44	1130.49	2
5.	14:00	118	43	45	1256.1	3
6.	15:00	105	41	41	753.66	3
7.	16:00	98	40	39	502.44	2
8.	17:00	92	40	38	376.83	2

Table 2 shows that while the day goes on and the water temperature rises, the electricity generated by the photovoltaic panel likewise rises. The water flow rate increased during the day and reduced with a drop in temperature as a result of the pump's higher DC voltage.

Table 2. Water temperature with flow rate and power produced

Time of day (Hrs)	Water temperature (ºC)	Water flow rate (ml/minute)	Power Producedby PV panel (Watt)	Recovery of water (%)
10:00	35	1440	185	5.9
11:00	37	1600	202	5.62
12:00	43	1660	210	6.62
13:00	44	1740	220	6.55
14:00	45	1700	200	6.94
15:00	41	1660	175	6.32
16:00	39	1600	160	6.12
17:00	38	1520	125	6.05

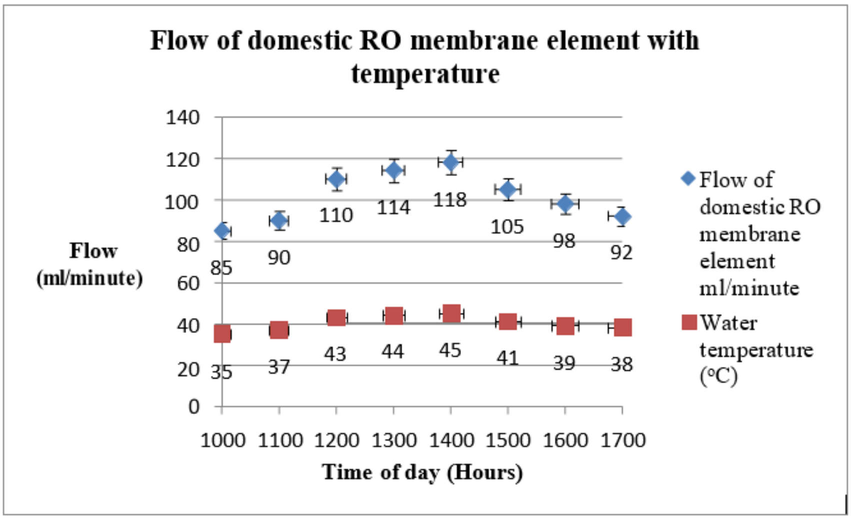


Figure 2. Flow performance of domestic RO membrane with temperature

As the temperature of the feed water rises from 35 OC to 45 OC, Figure 2 illustrates how the permeate water flow rate of the home RO membrane element increases from 85 ml/minute to 118 ml/minute. The temperature and flow measurements are within the 1.5% error zone, and error bars are also displayed. The amount of permeate water produced overall rises by 20% throughout the span of seven hours, from 10:00 to 17:00. The curve fitting demonstrates that the feed water's temperature and flow follow a parabolic trajectory as they rise and fall throughout the day. In the case of flow performance, the R2 value is around 0.87, indicating a good match; in the case of temperature, it is approximately 0.85. The R2 value's variation from 1 represents a variety of uncontrollable factors, including changes in wind speed and solar radiation intensity, in addition to the experimental error.

4.2 Improvement in Photovoltaic Panel Performance

Over time, data on the electricity generated by solar panels with and without cooling has been gathered. The home RO membrane element's feed water is utilized for cooling. Figure 3 shows that when solar panels are cooled, they generate more electricity overall compared to when they are not cooled. The power generated with and without cooling is within the 2% error zone, as indicated by the displayed error bars. There have been seen average increases in power generation of 8–10%. As a result, the efficiency of solar panels has improved.

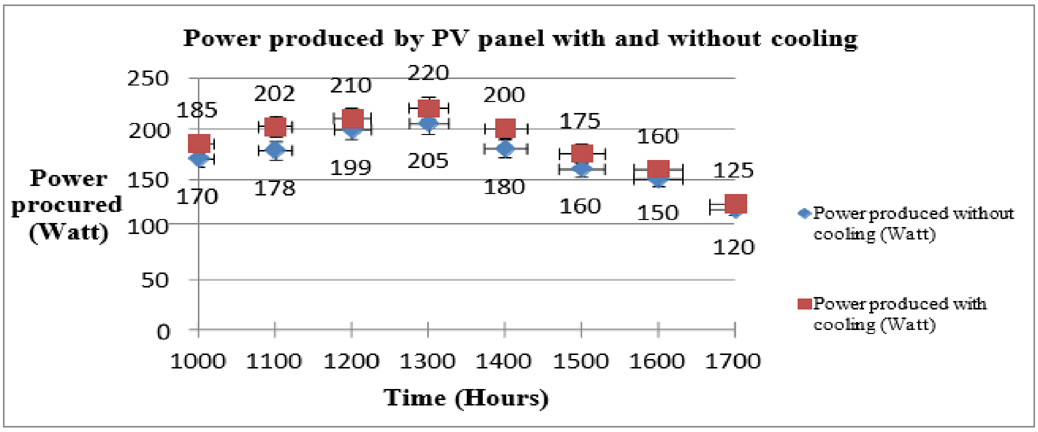
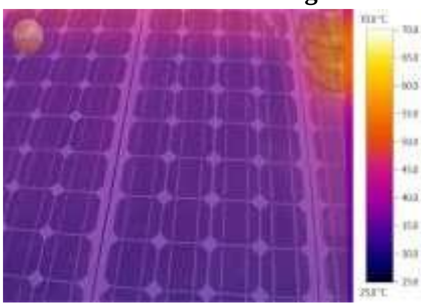
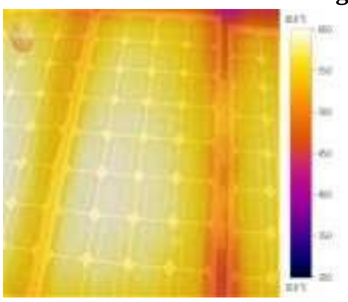
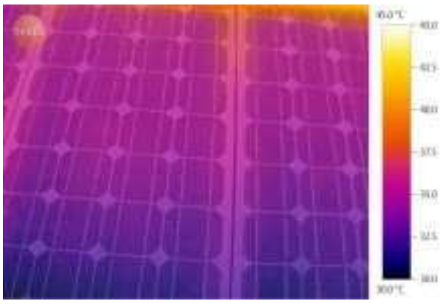
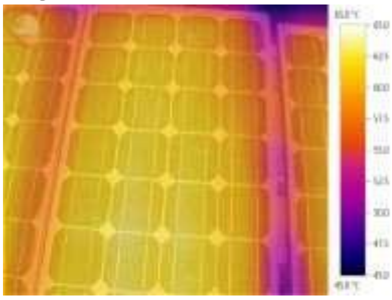


Figure 3. Power produced by PV panel with and without cooling

Time	With cooling	Without cooling
11:00 Hrs	 Avg.36.4ºC	 Avg. 55.5º C
12:00 Hrs	 Avg. 34.3ºC	 Avg. 59.1ºC

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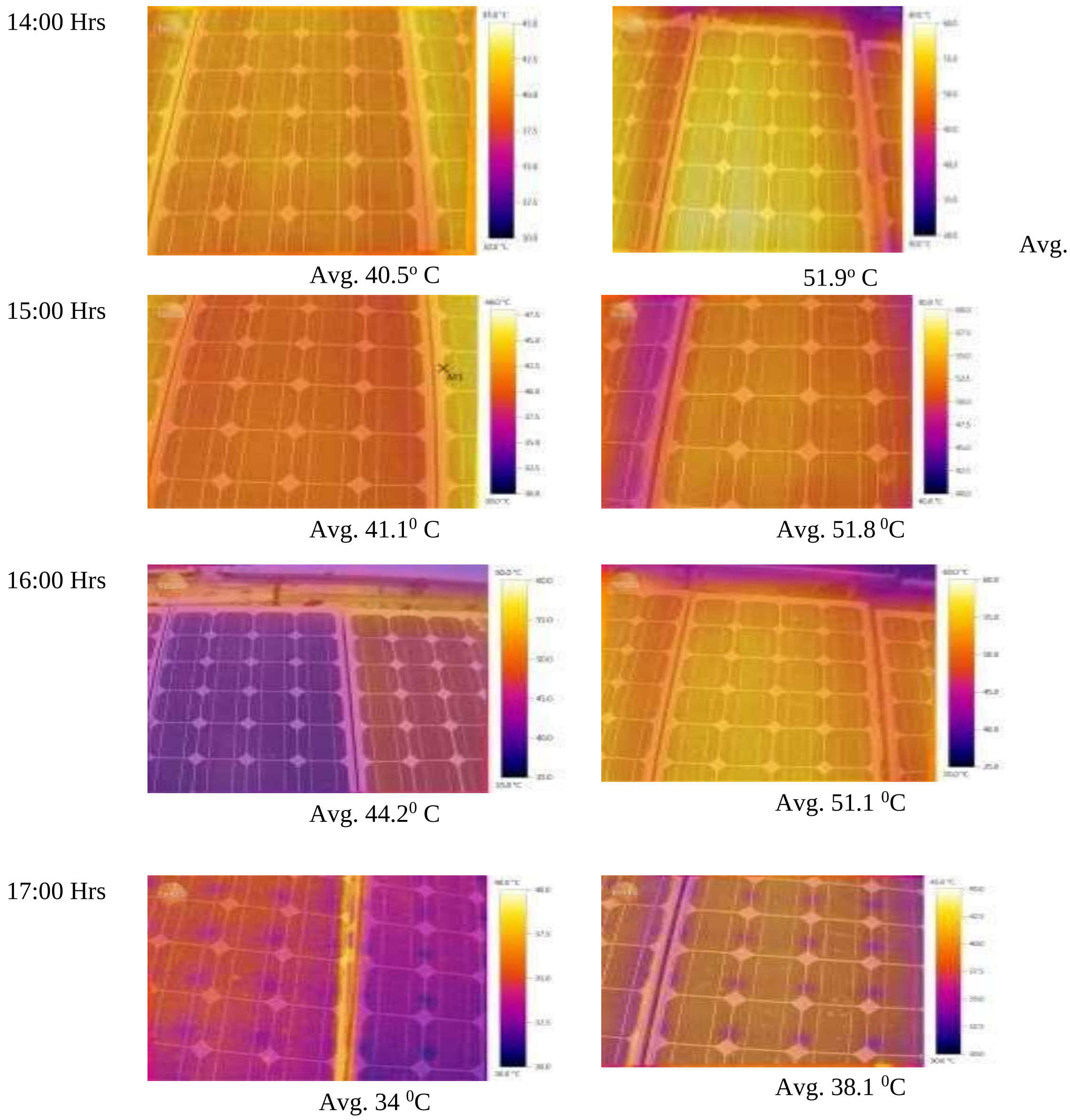

Figure 4. Thermal images of PV panel with and without cooling at different time during the day

Figure 4 illustrates how a solar panel's temperature may be regulated by cooling the panel from the back. At 1200 hours, the panel without cooling had a temperature of 59.1 ^{0}C, whereas the panel with cooling had a temperature of 34.3 ^{0}C at the same moment. As a result, there was around a 25^{0}C difference in panel temperature with and without cooling. Nevertheless, by 14:00 hours, there was only around a 12^{0}C difference in panel temperature between those with and without cooling. This is a result of the temperature of the feed water rising.

The thermal energy collected has been effectively used to reduce the energy consumption of reverse osmosis. Table 1 shows that when the temperature rises from 350°C to 450°C, the flow increases from 85 ml/minute to 118 ml/minute. This means that a 12-watt residential RO pump must operate for 196 hours to create one cubic metre of water with an 85 ml/minute flow rate, but the same pump must run for 141 hours to produce one cubic metre of water with a 118 ml/minute flow rate. Thus, the energy required to create a cubic metre of fresh water by residential RO drops from 2.352 Kilowatt-hour to 1.694 Kilowatt-hour, representing a 28% reduction in energy usage.

When the temperature rises from 35 ^{0}C to 45^{0}C, the dynamic viscosity of water falls from 0.7194 mPa-s to 0.5960 mPa-s [3]. The drop in viscosity signifies a decrease in flow resistance, which results in improved flow performance of the membrane.

Thus, it has been proved that thermal energy from a solar panel may be harvested by employing feed water to reverse osmosis as a cooler. The available feed water was used to solve the actual problem. It is understandable that if the feed water temperature is lower, the solar panel temperature can be more effectively managed, and the differential feed water temperature would rise as a result.

5. CONCLUSION

The temperature of the photovoltaic panel was regulated by flowing water on the rear side of the panel, and thermal energy was collected from the solar photovoltaic panel and used for productive purposes. Domestic reverse osmosis RO membrane permeate flow rate rose with increasing water temperature from 85 ml/minute at 35 ^{0}C to 118 ml/minute at 45^{0}C This suggests that tapped heat energy in feed water to reverse osmosis improves reverse osmosis membrane productivity by lowering feed water viscosity. The cooling water may regulate the temperature of the PV panel.

The difference in average temperature of PV panels with and without cooling is greatest around 1200 midday, when the temperature of PV panels with cooling was 34.3^{0}C and without cooling was 59.1^{0}C. As the temperature of the PV panel remained low, the power produced by it was boosted by cooling on the rear side. Heating feed water for solar photovoltaic panel cooling boosted total water flow by 20% during a 7-hour period. It has been proven that increasing the feed water temperature by 100 ^{0}C reduces the specific energy consumption of reverse osmosis by approximately 28%.

As a result, the suggested method displays a win-win combination of increased solar panel efficiency and thermal energy recovery. As a result, it opens the door to more research into designing systems with improved energy efficiency in order to reduce greenhouse gas emissions.

REFERENCES

[1] Abdelrahman Aburub et al., “Experimental Investigations of a Cross-Flow Humidification Dehumidification Desalination System,” International Water Technology Journal, vol. 7, no. 3, pp. 198-208, 2017.

[2] Naseer Ahmad, “Modeling, Simulation and Performance Evaluation of a Community Scale PVRO Water Desalination System Operated by Fixed and Tracking PV Panels: A Case Study for Dhahran City, Saudi Arabia,” Renewable Energy, vol. 75, pp. 433-447, 2015.

[3] Kavita Joshi et al., "Maximum Power Operation of a PV System Employing Zeta Converter with Modified P&O Algorithm," International Journal of Engineering Trends and Technology, vol. 70, no. 7, pp. 348-354, 2022.

[4] Farah Ejaz Ahmed, Raed Hashaikeh, and Nidal Hilal, “Solar-Powered Desalination–Technology, Energy and Future Outlook,” Desalination, vol. 453, pp. 54-76, 2019.

[5] M.A. Alghoul et al., “Design and Experimental Performance of Brackish Water Reverse Osmosis Desalination Unit Powered by 2 KW Photovoltaic System,” Renewable Energy, vol. 93, pp. 101-114, 2016.

[6] Kyaw Thu, Yin Maung Maung, and Than Than Win, "Modelling of a Solar Cell Considering Single-Diode Equivalent Circuit Using Matlab/Simulink," SSRG International Journal of Electronics and Communication Engineering, vol. 6, no. 6, pp. 5-9, 2019.

[7] Ehab S. Ali, “Recycling Brine Water of Reverse Osmosis Desalination Employing Adsorption Desalination: A Theoretical Simulation,” Desalination, vol. 408, pp. 13-24, 2017.

[8] Arvind Prabhakar, "CFD Analysis of Static Pressure and Dynamic Pressure for NACA 4412,” International Journal of Engineering Trends and Technology, vol. 4, no. 8, 2013.

[9] Ines Ben Ali, “Systemic Design of a Reverse Osmosis Desalination Process Powered by Hybrid Energy System,” International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), pp. 1-6, 2014.