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Thermo-Economic Assessment of Photovoltaic/Thermal Pan-Els-Powered Reverse Osmosis Desalination Unit Combined with Preheating Using Geothermal Energy

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Abstract: Recently, the reverse osmosis (RO) process is widely used in the field of desalinating brackish water and seawater to produce freshwater, but the disadvantage of using this technology is the increase in the rates of electrical energy consumption necessary to manage these units. To reduce the rates of electrical energy consumption in RO desalination plants, geothermal energy and photovoltaic/thermal panels were used as preheating units to heat the feed water before entering RO desalination plants. The proposed system in this study consists of an RO desalination plant with an energy recovery device, photovoltaic/thermal panels, and a geothermal energy extraction unit. To evaluate the system performance, three incorporated models were studied and validated by previous experimental data. The results indicated that incorporating the geothermal energy and photovoltaic/thermal panels with the RO desalination plants has positive effects in terms of increasing productivity and reducing the rates of specific power consumption in RO desalination plants. The average saving in the specific power consumption for utilizing the thermal recovery system of PV panels and geothermal energy as preheating units reached 29.1% and 40.75% for the treatment of seawater and brackish water, respectively. Additionally, the economic feasibility showed the saving in the cost of freshwater produced from the RO desalination plants for incorporating both geothermal energy and photovoltaic panels with a thermal recovery system with reverse osmosis desalination plants of up to 39.6%.

Keywords: RO desalination system; photovoltaic/thermal panels; geothermal energy; productivity improvement; economic analysis; energy saving

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1. Introduction

Recently, due to the continuous climatic changes and rapid population growth, potable water does not meet the daily requirements, especially in the Middle East and North Africa region. Therefore, there has been an urgent need to innovate an environmentally friendly desalination technology in order to desalinate seawater, brackish water, and groundwater in order to overcome the problem of fresh water shortage, in addition to limiting climate changes. Meanwhile, recently, reverse osmosis membranes have been widely used in the production of potable water, by treating brackish water, seawater, and groundwater. Therefore, the top priority at that time is to enhance the operating and design parameters of RO desalination plants in order to increase their productivity of pure water and save energy consumption rates [1,2]. Additionally, the temperature of the feed water is one of the most important operating factors that have a significant impact on the performance of reverse osmosis plants [3]. As a result of climatic changes throughout the year, the feed water temperatures of the reverse osmosis plants change throughout the year with the change in the seasons of the year. The performance of the reverse osmosis plants was studied throughout the year to show the positive and negative effects of changing the feed water temperatures due to climatic changes throughout the year. According to the study's findings, reverse osmosis plants' productivity increased by up to 3% for every degree Celsius that feed water's temperature rose as a result of climate change [4], but water quality decreased as a result of higher salt permeability rates across the membrane with higher feed water temperatures [5], higher osmotic pressure with higher temperatures [6], and a decrease in liquid viscosity with temperature increase, and this leads to an improvement in high-pressure pump efficiency [7] and the efficiency of energy recovery devices [8]. Reverse osmosis desalination technologies have spread widely to produce fresh drinking water. That was recently; therefore, the top priority now is to devise various optimization techniques to increase the productivity of this type of plant and reduce energy consumption rates through sustainability criteria. The temperature of feed seawater is one of the important operating variables that have a direct impact on reverse osmosis (RO) plants' performance. Therefore, the performance of RO desalination units was evaluated throughout the four seasons of the year in order to show the general positive and negative effects on the performance of this type of unit.

Shalaby et al. [9] empirically studied the performance of an RO desalination unit powered by a photovoltaic/thermal panel. Abdelgaied et al. [10] theoretically studied the impacts of preheating technology on power consumption rates of an RO unit. They found that the saving in the power consumption rates of the RO desalination unit were varying between 18.69% and 22.87% and 24.33% and 35.79% for the cases of treating seawater and brackish water, respectively, compared with a conventional RO unit without a preheating unit. Goi et al. [11] studied the effect of forward osmosis advanced spacers on the performance of a reverse osmosis desalination system. They found that the saving in the rates of power consumption reached 9.27% for utilizing the advanced spacers. Jamshidian et al. [12] mathematically studied the influences of the thermal energy storage system incorporated with solar concentrators on the performance of a hybrid RO-MED desalination system. They concluded that the optimum recovery can be adapted when the desalination plant operated at 50% capacity, leading to a 15% rise in total recovery compared with the only MED unit. Additionally, using the thermal energy storage can extend the working hours by 30%. Abdelgaied et al. [13] mathematically examined the influence of incorporating the HDH desalination unit with an RO desalination system combined with solar collectors. They conducted the utilization of this hybrid HDH-RO desalination unit combined with solar collectors, which reduced the specific power consumption by a rate varying between 14.7% and 65% as compared with the only RO unit. Shakib et al. [14] theoretically studied the influences of waste heat recovery from a gas turbine cycle on the performance of a hybrid MED-TVC + RO desalination plant. They concluded that instilling the hybrid MED-TVC + RO desalination plant on the exhaust gas line will reduce the production of CO_2 by 10.5% and 11.5% of the volume fraction for oil and natural gas, respectively. Hosseinipour et al. [15] empirically examined the performance of an RO desalination system with a spiral wound membrane combined with single-acting, free-piston energy recovery. Kumar et al. [16] theoretically conducted a performance of an HDH system and RO desalination system incorporating the organic Rankine cycle to produce drinking water and generate electricity. Park et al. [17] theoretically studied the behavior of the batch RO desalination unit with a free piston. They found that the batch RO desalination unit with 80% recovery can produce permeate water with minimum power consumption rates. Heidary et al. [18] conducted a behavior of a hybrid RO-MSF plant powered by renewable energy sources (solar and wind energies). Sadri et al. [19] mathematically studied the behavior of hybrid MED-TVC + RO desalination. Sadri et al. [20] conducted a thermodynamic and exergetic analysis of the behavior of the hybrid systems of multieffect distillation, adsorption desalination, and reverse osmosis. Iaquaniello et al. [21] conducted the behavior of a hybrid MED-RO desalination system combined with parabolic concentrators. They concluded that these hybrid systems are an effective way to reduce the costs of water production for a small-scale plant and not only for large-scale plants. Rashidi et al. [22] presented a comprehensive review of RO desalination systems powered by wind energy. Saeed et al. [23] conducted a performance of the FO-RO system. They concluded that using the FO-RO system will increase the quality and productivity, as well as decrease power consumption by a rate of up to 0.9 kWh/m^3. Mansour et al. [24] empirically examined the impact of an energy recovery device on the rates of energy consumption in an RO unit. The outcomes presented that the saving in power consumption reached 80% for incorporating the energy recovery device with the RO unit. Abdelgaied et al. [25] theoretically studied the behavior of a hybrid HDH-RO desalination system combined with photovoltaic/thermal panels and solar dish concentrators. Fu and Zhou [26] theoretically studied the performance of a real-world 47-bus distribution network of greenhouses covered with three photovoltaic panels in northern China. They found that the saving in energy cost reached 15% for covering the greenhouse with a 25% photovoltaic coverage ratio. Chow [27] presented a comprehensive study on the performance of solar photovoltaic/thermal hybrid technologies. Fu [28] introduced the statistical machine learning technique for the stochastic planning of distribution networks by considering uncertainties in photovoltaic power. Ibrahim et al. [29] presented a comprehensive review of a flat plate photovoltaic/thermal solar collector that produces both electricity and thermal energy simultaneously. Abdelgaied et al. [30] experimentally studied the influences of energy storage materials and an evaporative cooler as a precooling unit on the performance of solar power membrane distillation. They concluded that the freshwater productivity and gain output ratio of the membrane distillation improved by 47.48% and 45.84%, respectively, for incorporating the energy storage materials and evaporative cooler with the membrane distillation unit. Kabeel et al. [31] studied the performance of a solar-assisted membrane distillation system integrated with an evaporative cooler as a precooling unit to cool the cooling water before it enters the direct contact membrane distillation unit. Abdelgaied et al. [32] presented a comprehensive review of the different improvement technologies that were utilized to improve the performance of membrane distillation systems.

Based on the literature that was reviewed in depth above, it is concluded that reverse osmosis desalination systems represent a good choice and have been widely used in the production of potable water by treating brackish water, seawater, and groundwater. Whereas reverse osmosis desalination systems represent one of the appropriate solutions for future technologies to overcome the problem of water scarcity, especially in the MENA region, they still need a lot of research to improve their productivity and reduce their rates of electrical power consumption. Therefore, the present theoretical study aims to incorporate the photovoltaic/thermal panels and geothermal energy with the RO desalination unit as a preheating unit to heat the feed water before entering an RO desalination unit using geothermal energy. This will increase the productivity rates of potable water and reduce the power consumption rates in RO desalination plants. The presently proposed hybrid system consists of PVT panels, geothermal energy, and the RO desalination unit with an energy recovery device. In the presently proposed RO desalination cycle, the thermal recovery system and the geothermal energy were utilized as heat sources to preheat the feed water before pumping it to the RO desalination unit.

2. System Description

The Middle East and North Africa region is one of the first countries in the world to suffer from water poverty as a result of climate change and population increase. Meanwhile, reverse osmosis desalination systems are among the most popular desalination systems used to treat brackish water, seawater, and groundwater. Therefore, this study aims to devise environmentally friendly improvement methods to improve the productivity of reverse osmosis units and reduce their electrical energy consumption rates. To achieve this idea, the geothermal energy and thermal recovery system of photovoltaic/thermal panels as renewable thermal energy sources were incorporated with the RO desalination unit to preheat the feed water before entering the RO desalination unit using geothermal energy. This will cause an increase in the productivity rates of potable water and reduce the rates of power consumption. Simplified schematics of the proposed RO desalination cycle incorporated with the geothermal energy and the photovoltaic/thermal panels are shown in Figure 1. The proposed system consists of photovoltaic/thermal panels, geothermal energy, and an RO desalination unit with an energy recovery device. The feed water is first preheated in the thermal recovery device of the photovoltaic/thermal panels, as well as two cool PV panels to increment the rate of output electricity. After that, the feed water is heated using geothermal energy to raise the feed water temperature before its pumping into the RO desalination unit with a PX pressure exchanger energy recovery device.

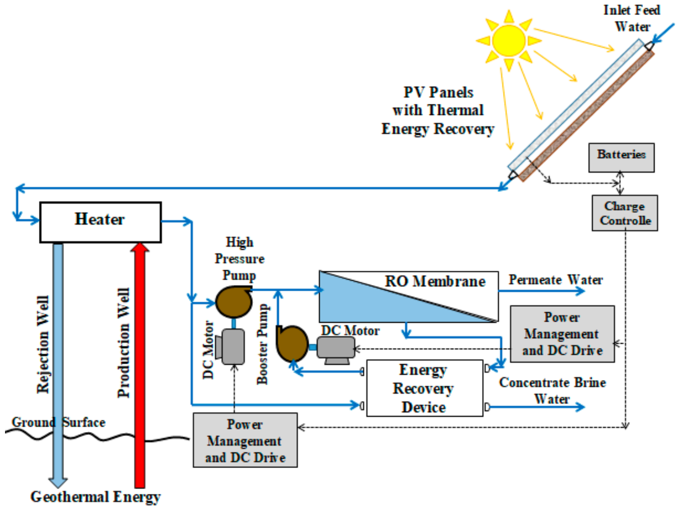

Figure 1. Simplified schematics of the proposed RO desalination cycle.

3. Mathematical Modeling

This section presents the models for photovoltaic/thermal panels, geothermal energy, and an RO unit with energy recovery.

3.1. Modeling of the Photovoltaic/Thermal Panels

The thermal efficiency of the photovoltaic/thermal panel η_{th} is calculated as follows [10,13,25]:

$$\eta_{th} = \frac{Q_{u,th}}{G_b \times \sum(A_p)} \tag{1}$$

where $\sum(A_p)$ is the sum of the surface area of the PV panel (m^2), G_b is the beam solar radiation (W/m^2), and $Q_{u,th}$ is the rate of useful thermal energy (W) calculated as follows:

$$Q_{u,th} = \dot{m}_w \, C_{p,w} \, (T_{w,out} - T_{w,in}) \tag{2}$$

where $C_{p,w}$, $\dot{m}_w$, $T_{w,in}$, and $T_{w,out}$ are the feed water heat capacity (J/kg °C), feed mass flow (kg/s), inlet feed temperature (°C), and outlet feed temperature (°C), respectively.

The electrical efficiency of the PV panel η_{elec} is calculated as [10,13,25]:

$$\eta_{elec} = \frac{I_{MPP} \times V_{MPP}}{G_b \times \sum(A_p)} = \eta_{ref}\left[1 - \beta_{ref}\left(T_{p,m} - T_{ref}\right)\right] \tag{3}$$

where I_{MPP} and V_{MPP} are the current and voltage, η_{ref} is the reference efficiency, $T_{p,m}$ is the panel mean temperature (°C), β_{ref} is the temperature coefficient, and T_{ref} is the reference temperature (°C) at STC.

3.2. Modeling of Geothermal Energy

The energy balance equations are:

$$\dot{m}_w\, C_{p,w}\, (T_{w,\,out} - T_{w,,in}) = \dot{m}_{gw}\, C_{p,gw}\, \left(T_{gw,\,in} - T_{gw,out}\right) \quad (4)$$

where $\dot{m}_{gw}$ is the mass flow rate of ground fluid, $T_{gw,\,in}$ is the inlet hot geothermal fluid (°C), and $T_{gw,\,out}$ is the outlet hot geothermal fluid (°C).

3.3. Modeling of RO Unit with Energy Recovery

The mass flow rate of permeate water ($\dot{m}_p$) is calculated as [10,13,25]:

$$\dot{m}_p = A_m\, k_w\, (\Delta P - \Delta\pi) \quad (5)$$

The recovery rate (RR) % is calculated as:

$$RR = \frac{\dot{m}_p}{\dot{m}_f} \quad (6)$$

The average transmembrane pressure ΔP (kPa) is calculated as [10,13,25]:

$$\Delta P = P_f - P_p - \left(\Delta P_{drop}/2\right) \quad (7)$$

The pressure drop across the membrane channel ΔP_{drop} (kPa) is calculated as [10,13,25]:

$$\Delta P_{drop} = 9.5 \times 10^8 \times \left(\frac{\dot{m}_f - \dot{m}_b}{2\,\rho}\right) \times 1.7 \quad (8)$$

The feed osmotic pressure π_f (kPa) is calculated as [10,13,25]:

$$\left\{ \begin{array}{ll} \pi_f = 206.4 \times \left(320 + T_{fw}\right) \times C_{s,f} & \left(for\ C_{s,f} < 20\,000 \frac{mg}{liter}\right) \\ \pi_f = 206.34 \times \left(320 + T_{fw}\right) \times \left(1.17\, C_{s,f} - 3.4\right) & \left(f,o,r,\ ,C_{s,f},>,20,\ ,000,\ \frac{mg}{liter}\right) \end{array} \right\} \quad (9)$$

The osmotic pressures on the average feed side and permeate π_{cave} and π_P (kPa) are calculated as [10,13,25]:

$$\pi_p = \pi_f (1 - SR) \quad (10)$$

$$\pi_{cave} = \pi_f\, CP\, \frac{C_{s,fc}}{C_{s,f}} \quad (11)$$

The salt rejection (SR) (%) is calculated as:

$$SR = \left(1 - \left(\frac{C_{s,p}}{C_{s,f}}\right)\right) \times 100 \quad (12)$$

The specific power consumption (SPC) (kWh/m^3) is calculated as [10,13,25]:

$$SPC = \frac{\pi_f\, (RR + \beta_l)\, SR}{3600\, RR(1 - RR)(1 - (RR \times SR))\, \eta_{HP}} + \frac{\pi_f\, (1 - \eta_{PX})\, (1 - \beta_l)\, (1 - RR)\, SR}{3600\ \ RR\, (1 - (RR\, SR))\, \eta_{BP}} + \frac{0.5}{RR} \quad (13)$$

where η_{HP} is the efficiency of high-pressure pump, η_{PX} is the PX energy recovery efficiency, η_{BP} is the booster pump efficiency, and β_l is the leakage ratio.

The input data used for solving the mathematical models of the proposed system are presented in Table 1.

Table 1. Input data of proposed system.

Parameters		Values
	Photovoltaic Panels	
P_{max} at STC	Maximum power at STC	4 × 350 W
A_P	Panel surface area	1.955 m × 0.992 m
η_{ref}	Reference efficiency	0.22
β_{ref}	Temperature coefficient for electrical efficiency	0.0029 1/°C
T_{ref}	Reference temperature	25 °C

Table 1. *Cont.*

Parameters		Values
	RO unit with energy recovery device	
$\dot{m}_f$	Feed water flow rate	1.4 m^3/h
η_{BP}	Efficiency of booster pump	84%
η_{HP}	Efficiency of high-pressure pump	84%
η_{PX}	Efficiency of pressure exchanger	98%
P_p	Permeate pressure	150 kPa
β_l	Leakage ratio	4%
T	Feed water temperature	$T_{fw} = T_{w\text{-}out}$
A_m	Membrane area	1.2 m^2

4. Validation of the Models

To confirm the validity of the theoretical models of the hybrid system proposed in this study, Figure 2 presents a comparison between the results of the theoretical model of solar photovoltaic/thermal panels with the empirical data collected by Giwa et al. [33]. It is shown in Figure 2 that the maximum deviation between the proposed model results and empirical data is 3.60% Additionally, Figure 3 presents a comparison between the results of the theoretical model of the RO unit with an energy recovery device and empirical results derived by Harby et al. [34]. Meanwhile, it is shown in Figure 3 that the maximum deviation between the proposed model results and empirical data is 2.38%.

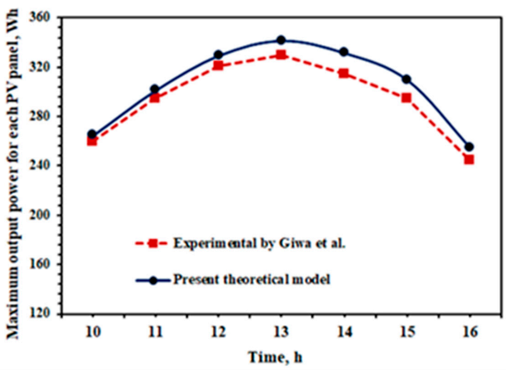

Figure 2. Model validation of the solar photovoltaic/thermal panels [33].

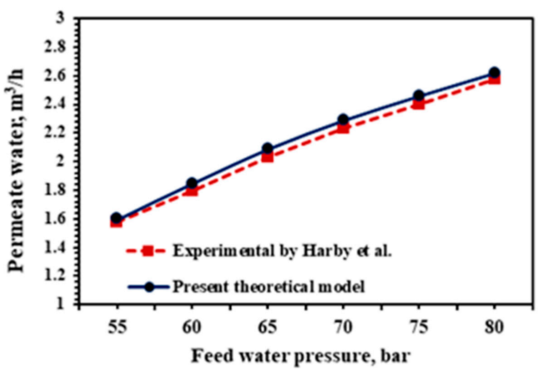

Figure 3. Model validation of the RO desalination unit [34].

5. Results and Discussions

To illustrate the influence of utilizing the thermal recovery system of PV panels and geothermal energy as preheating units on the specific power consumption rates of an RO unit, Figure 4 shows the hourly variation of solar radiation intensity, ambient air temperature, and feed water temperature supplied to the RO desalination unit from the period of 10:00 a.m. to 4:00 p.m. under meteorological Egyptian conditions. As shown within the period of 10:00 a.m.–4:00 p.m., the solar radiation intensity rises gradually to reach a peak value of 1050 W/m^2 at 12:00 a.m. and gradually declines after that. Additionally, within the period of 10:00 a.m.–4:00 p.m., the temperature of the ambient air varies between 34 and 39 °C, and throughout the day, the supply water temperature in the RO desalination unit was kept constant at 50 °C by controlling the flow rate of hot water from the subsoil to the heat exchanger, which represents the primary heating unit for the feed water.

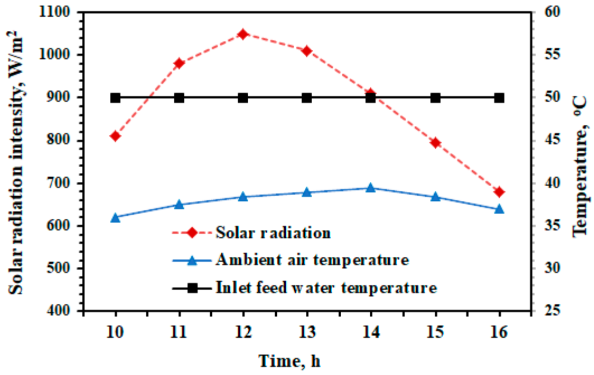

Figure 4. Variations of sunrays, ambient temperature, and feed water temperature.

In the proposed system, PV panels are used to produce the electricity required to run the pumps of the desalination unit, and to increase the rates of electricity generation, a thermal recovery unit was integrated with PV panels in order to reduce the PV cell temperature and thus raise the rate of output electricity. At the same time, the heat recovery unit represents the first preheating unit to heat the feed water before it enters a desalination system. Figure 5 shows an hourly variance of maximum electricity generated by PV panels and its efficiency for the cases with and without the thermal recovery system. As shown in Figure 5, during the period from 10:00 a.m. to 6:00 p.m., the maximum electricity produced by the PV panels in the case without using the thermal recovery system varied between 925 and 1065 watts, but for incorporating the thermal recovery system with photovoltaic panels, the rates, electricity generation was increased and ranged between 1060 and 1350 watts. The rate of improvement in electricity generation reached between 0.47% and 43.6% when incorporating the thermal recovery system with photovoltaic panels. This variation in the rates of improvement in electricity generation is due to the effect of changing the intensity of the incident solar radiation on the PV panels and the ambient air temperature. Meanwhile, at 10:00 a.m. and 4:00 p.m., the cell temperature of the PV panels without cooling is low, and therefore, the amount of improvement in the rates of electricity generation is low in the range of 0.47%. However, with the increase in the intensity of solar radiation, the cell temperature of the PV panels rises at great rates, and therefore, the use of cooling technology is very effective, as the rates of improvement in electricity generation reached 43.6%. Additionally, the electrical efficiency of PV panels without a thermal recovery system varied between 11.7% and 20.8%, but for incorporating the thermal recovery system with photovoltaic panels, the rates of electrical efficiency were increased and ranged between 16.7% and 20.9%.

Figure 6 shows the influences of preheating units on power consumption rates in the RO unit with an energy recovery device. As shown in Figure 6 for brackish water treatment, the SPC for the RO desalination unit with an energy recovery device reached 0.52 kWh/m^3 for the cases without utilizing preheating units (geothermal energy and thermal recovery system of PV panels), while for utilizing the thermal recovery system of PV panels and geothermal energy as preheating units, the SPC was reduced to 0.308 kWh/m^3. Additionally, for seawater treatment, the SPC for the RO desalination unit with an energy recovery device reached 2.75 kWh/m^3 for the cases without utilizing the preheating units, while for utilizing the thermal recovery system of PV panels and geothermal energy as preheating units, the SPC was reduced to 1.95 kWh/m^3. The saving in the specific power consumption for utilizing the thermal recovery system of PV panels and geothermal energy as preheating units reached 29.1% and 40.75% for seawater and brackish water treatment, respectively.

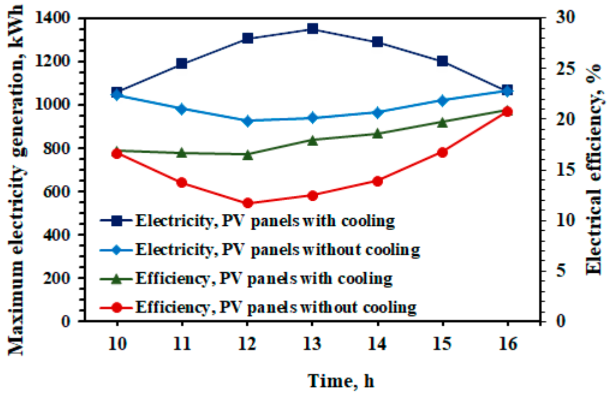

Figure 5. Variation of electricity generation and electrical efficiency from PV panels with and without the thermal recovery system.

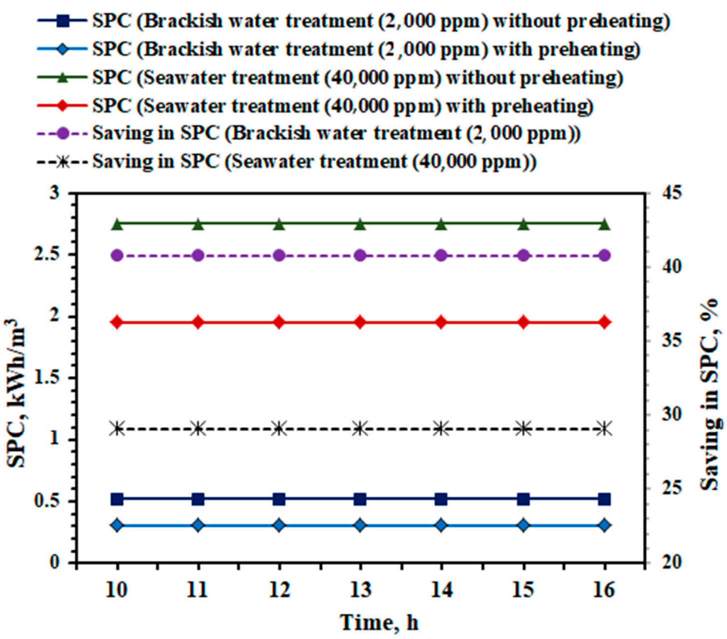

Figure 6. Variation of SPC and saving in SPC.

6. Economic Feasibility

To demonstrate the economic feasibility of incorporating both geothermal energy and photovoltaic panels with a thermal recovery system with reverse osmosis desalination plants, the cost of freshwater produced from the reverse osmosis unit was calculated based on the total cost of the entire system components and freshwater productivity rates using procedures of an economic analysis presented by Ammous et al. [35] (Table 2). Based on the details of the costs shown in Table 2, the cost of freshwater produced from the system proposed in this study was 0.966 \$/m^3 compared with 1.07 \$/m^3 for a PV/T-RO desalination unit connected with a solar concentrator presented by Abdelgaied et al. [25] and 1.6 \$/m^3 for a PV/T-RO desalination unit presented by Anand et al. [36]. The results of economic feasibility showed that incorporating both geothermal energy and photovoltaic panels with a thermal recovery system with reverse osmosis desalination plants represents an effective technology that reduced the cost of freshwater produced from the RO desalination plants by 9.7% compared with Abdelgaied et al. [25] and by 39.6% compared with Anand et al. [36].

Table 2. Details of the cost of the proposed system.

System Components	Description of Components	Cost ($)	
Photovoltaic panels with thermal recovery system	Four photovoltaic panels with charge controllers, solar batteries + thermal recovery system	2175	
Geothermal energy system	Heater + pipes	865	
RO desalination unit with energy recovery device	Membrane unit + energy recovery device + booster pump + high-pressure pump	2505	
		Cost of plant components ($)	5545
		Cost of maintenance ($)	1070
		Cost of installation ($)	970
		Replacement cost ($)	3252
	-	**Total cost of the plant ($)**	**10,837**
	-	**Permeate water capacity (m^3/year)**	**1038**
	-	**Permeate water cost ($/$m^3$)**	**0.966**

7. Conclusions

The current study aims to improve the water productivity of reverse osmosis plants, in addition to reducing their energy consumption rates, in order to overcome the problem of fresh water and energy shortages that most countries of the world suffer from, especially remote areas in the Middle East and North Africa. Additionally, the temperature of the feed water has been considered one of the most important operating factors that have a direct impact on the productivity of the reverse osmosis plants and their energy consumption rates. Therefore, this study dealt with the use of a thermal recovery system for photovoltaic/thermal panels and geothermal energy as preheating units to heat the feed water before entering the reverse osmosis unit in order to increase its productivity and reduce energy consumption rates in desalination plants using reverse osmosis technology. The proposed system consists of photovoltaic/thermal panels, geothermal energy, and the RO unit with energy recovery. In the presently proposed RO desalination cycle, the thermal recovery of PV/T panels and geothermal energy were utilized as heat sources to preheat feed water before pumping to RO plants. The main results are the following:

- The rates of electricity generation from the photovoltaic/thermal panels varied between 1060 and 1350 watts with an improvement rate reaching between 0.47% and 43.6% when incorporating the thermal recovery system with photovoltaic panels.
- The economic feasibility presents that the cost of freshwater produced from the RO desalination unit from the RO desalination plants for incorporating both geothermal energy and photovoltaic/thermal panels with reverse osmosis units reached 0.966 $/$m^3$ with a saving of up to 39.6%.
- The saving in the specific power consumption for utilizing the thermal recovery system of PV panels and geothermal energy as preheating units reached 29.1% and 40.75% for seawater and brackish water treatment, respectively.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A	surface area, m^2
C_{wm}	water concentration in membrane, mol/m^3
C_p	specific heat, J/kg °C
CP	concentration polarization factor, ppm
C_s	salt concentration, mg/liter or ppm
D_w	water diffusivity, m^2/s
G_b	direct beam solar irradiation, W/m^2
K_s	salt permeability coefficient, kg/m^2 s kPa
K_w	membrane permeability coefficient, kg/m^2 s kPa
$\dot{m}$	mass flow rate, kg/s
Q_{loss}	thermal energy losses, W
RR	recovery rate,-
SPC	specific power consumption, kWh/m^3
SR	membrane salt rejection,-
T	temperature, °C
UL	overall heat losses, W/m^2 °C
ΔP	average transmembrane pressure, kPa
ΔP_{drop}	pressure drop across the membrane channel, kPa
Greek letters	
η_{opt}	optical efficiency of the solar collector, %
η_{ref}	reference efficiency, %
β_{ref}	temperature coefficient for electrical efficiency, -
β_l	leakage ratio, %
δ_m	membrane thickness, m
π	osmotic pressure, kPa
μ_w	water viscosity, Pa·s
Subscripts	
p_w	pure water
f_w	feed water
in	inlet
a	air
$_{bw}$	brine water
Abbreviations	
PV	photovoltaic
PX	pressure exchanger
RO	reverse osmosis

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