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Improving the Performance of the Solar Panel Reverse Osmosis System Through the Return Water

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ABSTRACT

The water and energy crises are among the major challenges facing many regions of the world today, due to increasing demand and limited traditional resources. The integration of renewable energy sources and desalination technologies has been identified as a promising solution to mitigate these crises. In this study, a small-scale solar-powered reverse osmosis (RO) desalination system was installed in Baghdad, Iraq. The system, which utilizes photovoltaic (PV) panels, consists of two 100W PV panels, a storage battery, and an inverter. The TRNSYS software model was used to calculate the power generated by the PV cells and the amount of sunlight required to operate the RO system, which includes the RO cells, membranes, and ion exchange system. The system purifies brackish water with a turbidity of 1000-5000 mg/L (TDS). This paper identifies the process flow, estimates the sizes of the main system components, and presents some results obtained by comparing a grid-powered RO system with a solar-powered system. The PV system was operated for 8 hours, from 9 AM to 5 PM, during the summer months for three consecutive months (August, September, and October). The study also aimed to improve the performance of the panels by utilizing the wastewater and excess water that is recycled to cool the panels. The results obtained showed It is noted that cooling reduced the surface temperature by an average of (2-5 °C) for the three months. Increase in efficiency for three consecutive months (the eighth, ninth, and tenth) from 11.8% to 12.58% during the august month and from 10.97% to 11.21% during the September month (10.4% to 10.82%) during the October month.

1. INTRODUCTION

Water scarcity has become one of the most serious global challenges of the 21st century, with United Nations reports indicating that nearly two-thirds of the world's population is expected to face high levels of water stress by 2025 [1]. Desalination, the process of removing salts and impurities from seawater and brackish water, offers a sustainable solution to this growing problem. This is particularly critical in regions, such as the Middle East, North Africa, and some Asian countries, where existing freshwater supplies are inadequate to satisfy the demands of rapidly growing populations and developing industries [2]. Desalination is an important means to achieve water security in regions without traditional sources of fresh water. It has been integrated into water supply planning in countries like Saudi Arabia and Australia [3]. Over half of Saudi Arabia's national drinking water is desalinated [4]. This highlights the significance of desalination as a sustainable and secure source of water supply, particularly for arid or semi-arid locations. In addition, desalination also eliminates the impact of climate change and its water scarcity over periods of short term when this is in operation. In Australia, water desalination plants formed a part of the water supply infrastructure enabling supply during major droughts experienced in the decade beginning early in the 21st Century [5]. Desalination has become an important part of water management, as it provides access to fresh water regardless of climatic conditions and growing environmental uncertainties [6]. Doing so would offer more than just a solution to water shortages; it can also help stability and economic growth. It is desalination, by giving a secure and sustainable source of water that enables those most to help development, like agriculture, industry, or tourism. In countries such as the United Arab Emirates, farming in desert areas has been supported by desalination, thus decreasing dependence on food imports [2]. In addition, water-intensive industries such as petrochemical and other big industrial sectors need desalinated water to support their activities [7]. Even as it remains more expensive than other sources of water, technology has driven down the cost to operate desalination plants. Advances in membrane technology, especially in reverse osmosis (RO) membranes, have led to energy savings and reduced cost of water production [8]. Solar-based RO solutions are typically more efficient than conventional thermally driven desalination approaches and less costly. Further development of membrane technology and the ongoing decrease in solar power prices have also led to lower operational costs, rendering solar-powered RO systems as an economically viable alternative [2]. As an example, modern RO plants are able to produce potable water at around US$0.30/m^3, which is much cheaper than the cost of older conventional thermal desalination plants where it can go to over US$3/m^3 [6]. However, modern RO membranes can be fouled in various ways: foulants such as organic matter, sludge derived from dissolved salts, or micro-organics; a plug-flow layer of salt precipitates trapped on the inflow side of the membrane; and biological contamination like bacteria. They reduce system efficiency and increase operation and maintenance costs. A variety of mitigation techniques are employed to minimize these problems, such as chemical cleaning and pretreatment of feedwater in combination with anti-scaling additives [7]. Given the operational difficulties of biofilm-induced RO membrane fouling, this study explores ways in which excess and recycled water from the RO system can be used to enhance thermal and electrical performance of solar panels, as well as assess how it affects panel surface temperatures and system efficiency.

In recent years, more attention has been paid to opportunities of integrating renewable energy sources with the desalination technologies to minimize the costs of their operation and impact on the environment. Photovoltaic-powered reverse osmosis (PV-RO) systems are among other technologies that have attracted a lot of interest in utilizing PV energy owing to its high-energy yield and applies in remote or off-grid locations. The RO is now regarded as the most energy-efficient method of desalination and is popularly used together with solar PV to generate freshwater out of brackish or seawater resources [8, 9]. PV-RO systems are generally models that looked upon are PV panels, energy storage stations, pumps as well as membrane modules that transform solar energy into electricity to be used to run the desalination process. The performance of small-scale solar-powered RO desalination units producing up to 15 liters per day was analyzed, considering seasonal variations in solar irradiance, wind, and temperature. System efficiency, energy consumption, and water production were validated through lab experiments and MATLAB simulations. The study also explored improving renewable energy use and scaling standalone systems with predictive modeling and alternative storage methods [10].

This paper has discussed how to design an optimal hybrid renewable energy system to be installed to provide power to reverse osmosis desalination plant at Aurar, Saudi Arabia. It demonstrates that solar power, supplemented by wind power and storage will reduce the prices and fuel consumption and streamline the systems. As a rule, the hybrid systems are suggested as a possible and sustainable solution that will have low emissions and high desalination rates in remote locations [11]. A hybrid renewable energy system was simulated through the System Advisor Model (TRNSYS) to desalinate water, and it predicted both the technical performance and the energy generated and economic feasibility to explore the effectiveness of using renewable sources [12]. Other studies have demonstrated that incorporating revitalized energy could help inject more steadiness into the functioning and reduce expenses in distant areas. A layout and evaluation of a hybrid-powered reverse osmosis plant at a remote area in Newfoundland [13].

This is after previous research on hybrid solar-wind desalination plants and computer simulation method, where models such as TRNSYS are used to test the technical and economic performance [14]. Modeled and optimized the operation of solar PV-RO systems that are operational in farms and demonstrated that the use of solar energy can reduce grid dependency, lower the cost of operation, and guarantee the presence of irrigation water even when the grid is not available or when there are limited resources [15]. Although the high operating temperature, especially in hot regions like the Middle East, is an issue with PV-RO desalination systems, the efficiency of the PV panels is greatly influenced by high operating temperatures. High temperatures on the panel minimize the generation of electricity, thus limiting the operation of the desalination unit. A number of researchers have proposed that cooling methods will enhance the efficiency of PV systems and the overall productivity of a system. Nevertheless, the possibility of using the rejected water or return water of RO systems as a cooling medium of PV panels has not been adequately investigated in small-scale desalination facilities.

Thus, the primary goal of this research is to explore the possibility of enhancing the functionality of a solar-powered RO desalination system, involving the use of return water of an RO process to cool PV panels. This paper will seek to determine the impact of the cooling strategy on panel surface temperature, electrical efficiency, power production, and freshwater production within the climatic conditions of Baghdad, Iraq.

2. EXPERIMENTAL SYSTEM DESCRIPTION

2.1 Overall system architecture

The experimental system in the given study is a miniature solar-powered reverse osmosis (PV-RO) desalination model that will operate in decentralized or off-grid regions. The system combines panels of PV, elements that transform the energy, filters of water pretreatment, an RO membrane module, and a cooling system that makes use of the rejected RO water.

Figure 1 shows a prototype of the portable desalination unit that has been designed during this research project, whereas Figure 2 gives the schematic representation of the composite PV-RO system. It includes three components of the system architecture: Subsystems:

1. PV power generation subsystem that powers the desalination unit with electricity.
2. Water treatment and RO desalination subsystem, which is in charge of the filtration of feedwater and freshwater generation.
3. Water circulation and cooling subsystem, in which the rejected RO water is recycled, to lower the temperature of PV panels to enhance their operations.

Raw water will first circulate in a feed tank where it is pumped by the feed tank through a set of pretreatment filters to eliminate suspended particles, chlorine and organic contaminants. The filtered water is then pressurized and forced into the reverse osmosis membrane module whereby the water is divided into permeate (fresh water) and concentrate (brine). The freshwater obtained is captured in a storage tank whereas the discharged brine water is partially utilized in the cooling of PV panels.

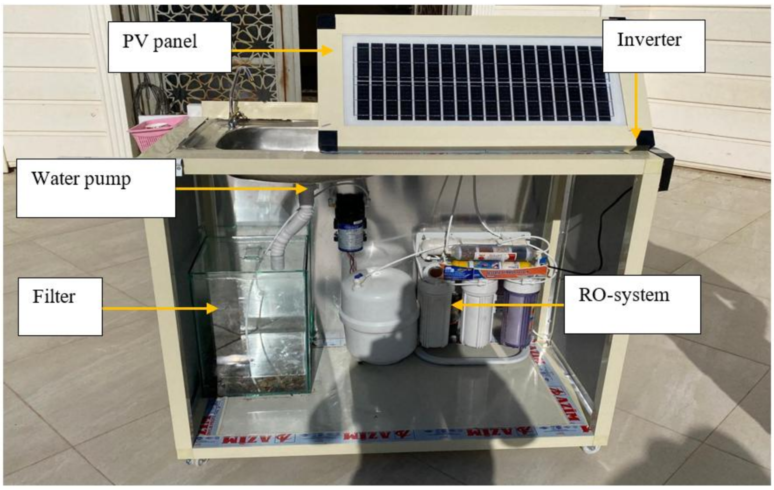

Figure 1. Portable desalination unit designed for the current study

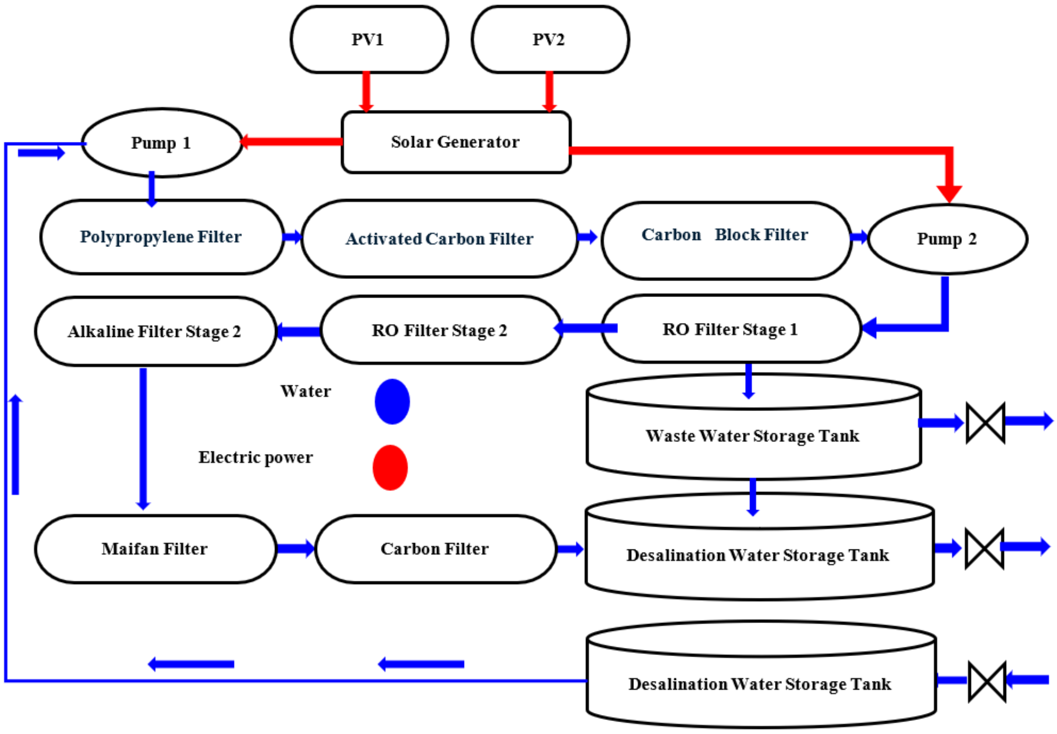

Figure 2. Schematic diagram of the portable desalination unit designed for the current study

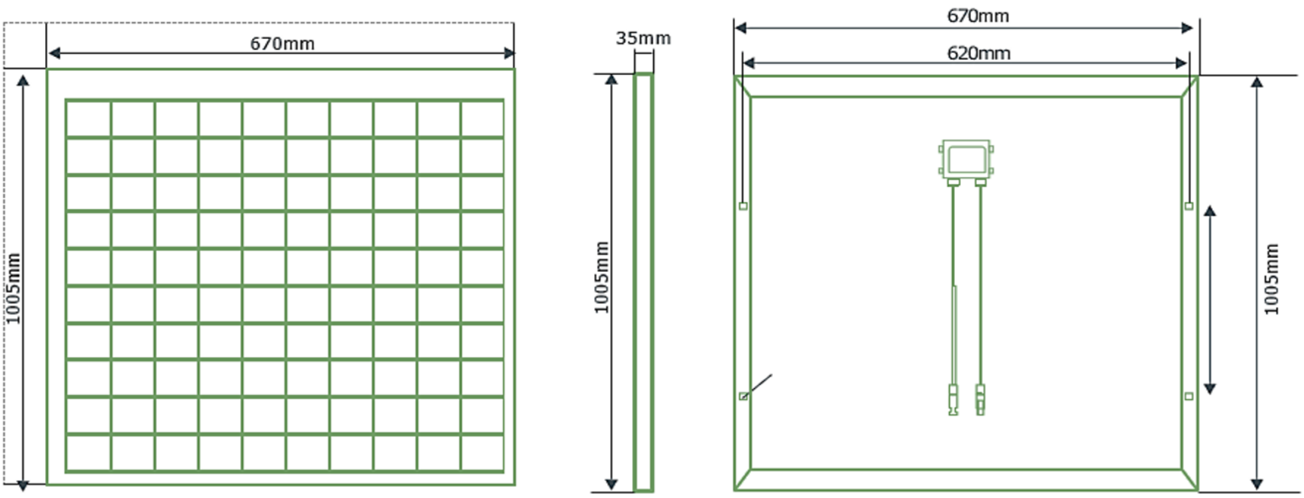

Figure 3. Dimensions of photovoltaic (PV) panel

2.2 Photovoltaic power subsystem

The desalination unit for this study was designed to be compact, easily transportable, and ideal for use in remote areas. The desalination process begins with a water storage tank, where the raw water is stored before treatment. The first pump is a brushless DC pump with the following specifications: maximum pumping height 300 cm, maximum flow rate 300 liters per hour, operating voltage 5 V DC, and maximum operating temperature 60 ℃. This pump is used to initially pressurize the water before it is directed through multiple filtration stages. The first stage includes a 5-micron polypropylene (PP) filter to remove large particles and sediment. The second stage is a coconut shell activated carbon filter to remove chlorine, chemicals, and odors. Finally, a solid carbon filter is used to provide further water purification. The entire system operates sustainably, powered by two solar panels. In the past decade, photovoltaic solar panels have emerged as a promising energy source worldwide. The only limitation associated with PV panels is their ability to generate electricity. Therefore, this study used two polycrystalline PV panels with dimensions shown in Figure 3 and Table 1. mounted on a metal bracket made of aluminum.

Table 1. Photovoltaic module specifications

Maximum Power	100 W
Tolerance	± 3%
Open Circuit Voltage	22 V
Short Circuit Current	6.06 A
Maximum Power Voltage	18 V
Maximum Power Current	5.56 A
Module Efficiency	14.9%
Solar Cell Efficiency	17.2%
Series Fuse Rating	15 A
Dimensions	1005 mm × 670 m × 35 mm
Weight	8 kg

The specifications of the two panels are one of the PV panels was dirty with dust, while the other was clean. This study explored the effects of dust accumulation on energy production and the efficiency of polycrystalline silicon solar panels placed indoors, which draw radiation from an array of LEDs to generate power. PV panels are devices used to convert sunlight directly into electricity using a technology known as solar cells or PV. The panels consist of an array of solar cells, typically made of silicon, a semiconductor element. When sunlight falls on the cells, photons (light particles) excite electrons inside the silicon, generating a direct current (DC).

Table 2. Operating and cleaning limits of the used reverse osmosis (RO) module

Maximum Operating Temperature	45 ℃
Maximum Operating Pressure	10 bars
Maximum Feed Flow Rate	7.6 L/min
pH Range, Continuous Operation	2-11
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance	< 0.1 ppm

2.3 Reverse osmosis desalination unit

The circuit diagram of the RO desalination system is shown in Figure 4, which comprises primarily pre-treatment, high-pressure DC pump, RO membrane, and post treatment. A commercial RO system module (the freshwater production rate being about 11.80 L/h) is used, operating for a PP sediment filter pre-treatment to filtrate out dirt, sand, rust and particulate matter in low-salinity water. This is then followed by a granular activated carbon (GAC) filter which takes out organic contaminates, and finally the CTO filter removes any degradation of taste or colour in your drinking water. A high-pressure DC pump (KJ-2500, 24 V voltage, 1.2 A current and a maximum flow rate of 1.60 L min $^{-1}$) was used in the experimental system along with a RO membrane unit (FilmTec™ BW60-1812-75). Table 2, the system operating conditions of the post-treatment unit consists of two carbon IAC-10 type integrated filters and one mineral filter. The saline water is fed through the pre-treatment unit and then into RO unit where fresh and brine will be extracted. The fresh water is then transmitted to the post-treatment unit as being potable, while the brine is ejected.

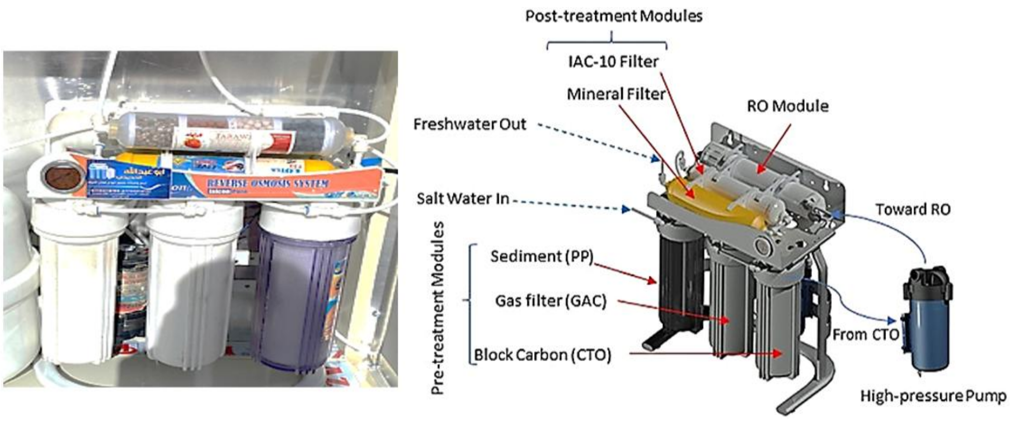

Figure 4. The main components of the brackish water reverse osmosis (BWRO) desalination

2.4 Measurement and instrumentation

In this study, we use a range of measuring devices to measure multiple variables such as (temperature, current, voltage, solar radiation, salinity, etc.). Table 3 provides details for each device.

3. METHODOLOGY AND DATA COLLECTION

The experimental tests were carried out in three months (August -October) in Baghdad. Operation of PV-RO desalination system was done on a daily basis (09:00 -17:00) with duration of operation being 8 hours when the solar radiation was the highest.

The measurements of solar radiation, panel temperature, voltage, current, and water production rate were recorded in 30 minutes intervals with precision meter and ohmmeter, and water generation rate tools in Table 3, respectively on every experimental day. The samples of feedwater were taken and examined to establish total dissolved solids (TDS), pH, electrical conductivity (EC), and salinity.

Table 3. Measuring and description devices

No.	Measuring Devices	Device Description
1	PH-W3988 Wi-Fi Water Quality Monitor	Equipment that allows real-time observation of six key water quality parameters, which include, pH, electrical conductivity, total dissolved solids, salinity, specific gravity (SG) and temperature.
2	Clap-meter	To measure the Voltage and current
3	Thermocouple	To measure the temperatures at the points of the two photovoltaic modules
4	Pyranometer	To measure solar radiance
5	Flow meter	To measure the flow rate

The mean salinity of the feedwater that was used in the experiment was between 1000 and 5000 mg/L TDS. It was also recorded on ambient temperature and the solar radiation conditions in order to measure the influence of the same on PV panels performance and productivity of the desalination process.

The current study has used a combination of design, implementation and data analysis in developing and evaluating a portable, solar-powered desalination unit that will be optimized to be used in off-grid applications in a variety of water sources. The design and operation of a RO desalination plant where PV solar energy would be used was the methodology used to provide sustainable and efficient water purification in Iraq. The design of the desalination system commenced with the choice of the components of the system, which consisted of the solar panels, charge controllers and pumps, and pre-filtration and RO filtration units. Initial design specifications were based on energy efficient design, durability and flexibility of the system to the changing environmental factors. The solar power generation system was constructed to fit the energy requirements of the RO desalination unit and pumps taking into consideration the levels of solar radiation, the rate of water demand, and the requirements of the desalination capacity. To collect and analyze data, the System Advisor Model (TRNSYS) software has been used to analyze the solar radiation data that would be applicable in the Baghdad area [12]. With this information, TRNSYS gave indications of the anticipated performance of the PV system in different sunlight conditions and made it possible to make changes in the size of the system to maximize power availability. Empirical evidence of the water quality in various sources was made by field tests on the installed system at Baghdad University. The obtained data was processed in order to estimate the desalination efficiency. Speaking of water quality, the highest quality of desalinated water was ascertained on the basis of the following parameters:

• TDS: Ideal drinking water is one with TDS of less than 500 mg/L [16].

• pH: 6.5 to 8.5: a positive pH of 7 is the optimal and desired range of drinking water [17].

• EC: EC in potable water is supposed to have values lower than 1000 µS/cm [18].

• Salt: Desalinated water must not contain too many salts, and the level of salts in the water should not exceed 500 mg/L to maintain the safety and the best flavor [19].

• Specific Gravity (SG): The SG of fresh water is supposed to be near 1.0, meaning that there are no excessive dissolved solids/impurities [20].

The electrical efficiency of the PV panels was calculated using the following equation:

$$\eta = \frac{P_{out}}{G \times A} \times 100 \tag{1}$$

where:

η = PV efficiency (%)
Pout = electrical power output of the PV panel (W)
G = solar radiation intensity (W/m²)
A = surface area of the PV panel (m²)

The electrical power output of the PV panel was determined from the measured voltage and current using:

$$P_{out} = V \times I \tag{2}$$

where, V is the panel voltage (V) and I is the current (A).

4. RESULTS AND DISCUSSION

4.1 Effect of ambient temperature

Climate conditions are one of the environmental factors that directly influence the efficiency of solar panels. Temperature can significantly affect the amount of energy produced by solar cells, whether made of crystalline silicon or other materials rely on the PV effect to convert light into electricity. As temperatures rise, solar cells undergo physical changes that lead to a decrease in their efficiency. This is primarily due to increased electron mobility within the semiconductor material, which leads to increased internal resistance and the loss of some of the resulting energy as heat. Figure 5 shows the air temperatures for three consecutive months (August, September, and October) from 9:00 a.m. to 5:00 p.m. It is noted that the highest temperatures were recorded in the eighth month, around midday, providing an initial indication of which month had the highest temperatures.

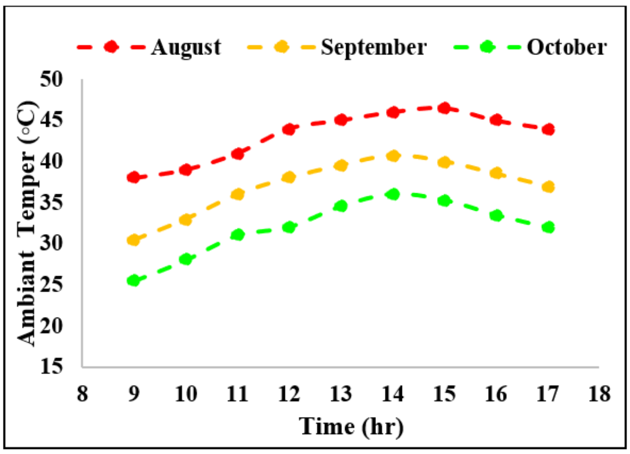

Figure 5. Ambient temperature in Iraq for August, September, and October

4.2 Solar radiation intensity

Solar radiation directly and positively affects solar cells by increasing the electrical power generated, but it indirectly and negatively affects their efficiency due to increased temperature. High solar radiation leads to greater power generation, while the resulting increased temperature reduces cell efficiency due to increased internal resistance. PV panels are exposed to multiple environmental factors that significantly impact their performance and efficiency. High solar radiation enhances the productivity of solar cells. PV panel production depends primarily on solar energy, or solar radiation, which is defined as the amount of solar radiation falling on a given area and capable of generating electrical energy. Figure 6 shows the radiation intensity trend for three consecutive months (the eighth, ninth, and tenth months) from 9:00 a.m. to 5:00 p.m. It is noticeable that the radiation intensity increases with time, reaching its highest value, recorded in the eighth month at approximately noon, then gradually decreases in the evening, providing an initial indication of which month has the highest radiation intensity.

The amount of solar radiation was gradually rising in the morning as well as at midday that was the maximum of the solar elevation angle. This is common to the patterns of the solar radiations in dry climates like Iraq. The greater the intensity of the radiation, the more the electrical power produced by the panels of PV. The more radiation however increases the temperature of the panel and this may lower conversion efficiency because of higher internal resistance in the PV cells. The same tendencies have been recorded in the PV-RO desalination systems that work in the Middle Eastern conditions [18].

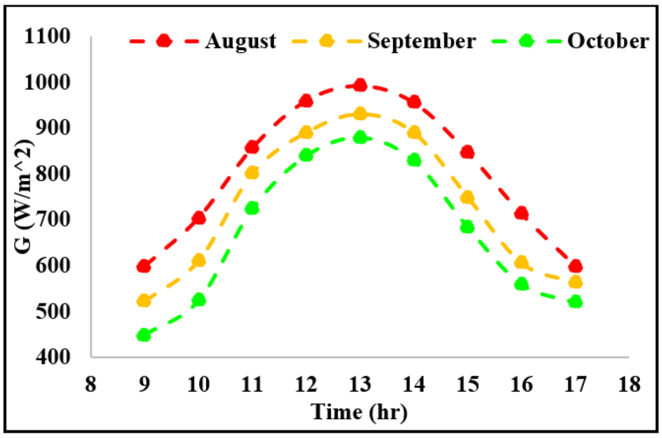

Figure 6. Solar radiation intensity in Iraq for August, September, and October

4.3 The effect of cooling on photovoltaic panel performance

Cooling is essential for solar cells because it improves their efficiency, as high panel temperatures lead to reduced energy production. Therefore, technologies resort to passive cooling (such as natural ventilation and heat sinks) or active cooling (such as pumping water and air) to maintain cell efficiency and extend their operational life. RO cooling can significantly improve solar cell performance, as high temperatures reduce efficiency, while cooling lowers their temperature. This results in increased electrical power generation, voltage, and current and improved cell life. Cooling the cells with water can significantly increase energy production, as solar cells operate more efficiently at lower temperatures. Figure 7 shows the effect of cooling on the panel surface temperature for three consecutive months (the eighth, ninth, and tenth months) from 9:00 a.m. to 5:00 p.m. It is noted that cooling reduced the surface temperature by an average of (2-5 °C) for the three months. Figure 7 shows the temperature change in PV panels surface with cooling and without the cooling system. These findings indicate that the RO system water was used to cool the panel by about 2-5 °C throughout the time of the experiments. This is a great reduction since as the temperature goes higher the PV cell efficiency reduces as the internal resistance increases in the semiconductor material. Consequently, the cooling plan will help in the enhancement of the electrical production and the overall performance of the entire system.

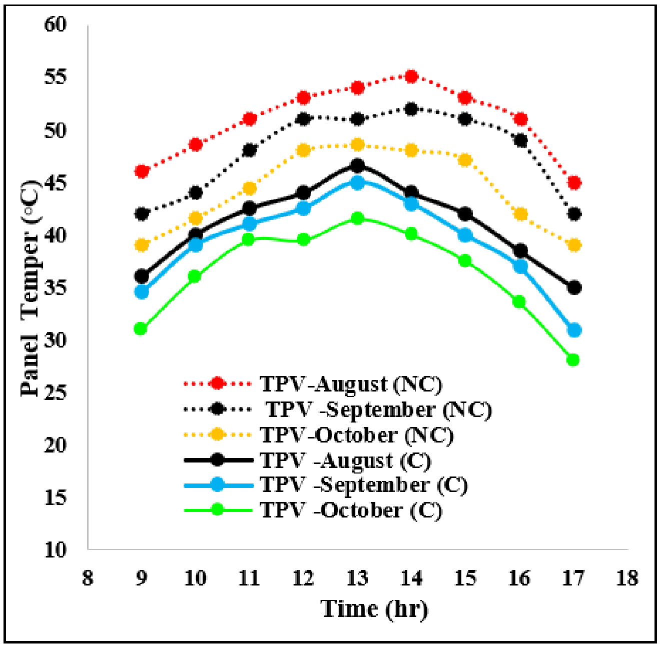

Figure 7. PV panels temperature with and without cooling

Another positive effect of reverse cooling on solar cells is increased energy production, as cooling lowers the temperature of the panels, increasing their efficiency. The current study showed an increase in electrical capacity of about 8.6% when the panels were cooled. Figure 8 shows the effect of cooling on the production capacity for three consecutive months (the eighth, ninth and tenth).

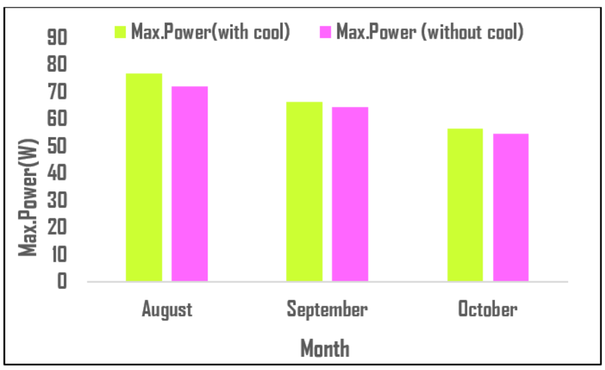

Figure 8. Photovoltaic (PV) panels maximum power with and without cooling

Another positive effect of reverse cooling on solar cells is increased efficiency, as cooling lowers the temperature of the panels, thus increasing their efficiency. The current study showed that cooling increases the efficiency of the panel. Figure 9 shows the increase in efficiency for three consecutive months (the eighth, ninth, and tenth) from (11.8% to 12.58%) during the august month and from (10.97% to 11.21%) during the September month (10.4% to 10.82%) during the October month.

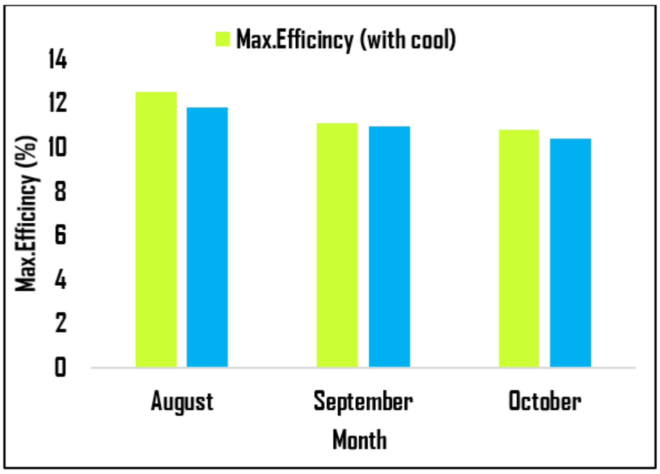

Figure 9. Photovoltaic (PV) panels efficiency with and without cooling

The implementation of the cooling with the implementation of the return water of the RO system lowered the surface temperature of the PV panels on about 2-5 °C during the experiment. This temperature drop enhanced the current flow of the electric components leading to greater top power rating of about 8.6 percent. This enhancement is enabled by the negative temperature coefficient of silicon solar cells whereby the high the temperature the lesser the voltage and the total efficiency. The same effects of water-based PV cooling have been reported in previous works discussing hybrid PV desalination PV systems.

4.4 Water production

Water production in a PV-RO (photovoltaic panels and reverse osmosis) system depends on the size and efficiency of the system, ranging from tens to thousands of tons per day. Production varies based on several key factors, including water pressure, operating temperature, feed water quality, membrane type used, and water recovery rate. The system combines the generation of electrical energy from solar panels to power the RO process, which purifies water through a semi-permeable membrane. Figure 10 shows the water production of an RO system using national electricity for a three-month period (August, September, and October) and a period extending from 9:00 AM to 5:00 PM. The maximum water production was achieved in the month of August, at an average of (8.9 L/h), while the lowest production was achieved in the month of (October) at an average of (7.8 L/h).

Figure 11 shows the water production of an RO system using photovoltaic panels for a three-month period (August, September, and October) and a period extending from 9:00 AM to 5:00 PM. The maximum water production was achieved in the month of August, at an average of (6.2 L/h), while the lowest production was achieved in the month of (October) at an average of (5.1 L/h). The main difference between the two systems is that the PV-RO system uses solar (PV) energy to operate the RO pump, providing sustainable water production independent of the national grid. The use of national electricity relies on the conventional electricity grid for water production, making it dependent on the availability of the electrical grid and potentially incurring ongoing electricity costs. The PV-RO system is a renewable energy solution, while the use of national electricity is a conventional solution. Figure 11 demonstrates the PV-RO system freshwater production per hour in three months of the experiment period. The outcomes that were obtained show that the maximum output has been achieved during August (6.2 L/h) because of the increase in the solar radiation and the sunshine duration. On the other hand, the level of production reduced in October (5.1 L/h) due to the decreased intensity of solar ray. This validates the fact that freshwater output in the PV-RO systems highly relies on the availability of solar energy that dictates the amount of electrical power that is given to the high-pressure pump.

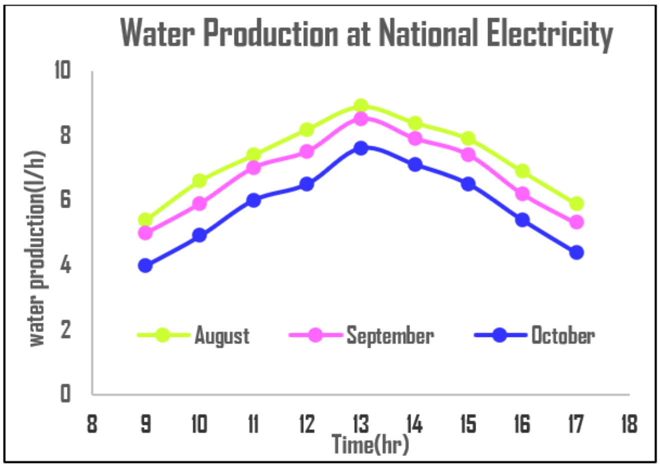

Figure 10. Water production at national electricity

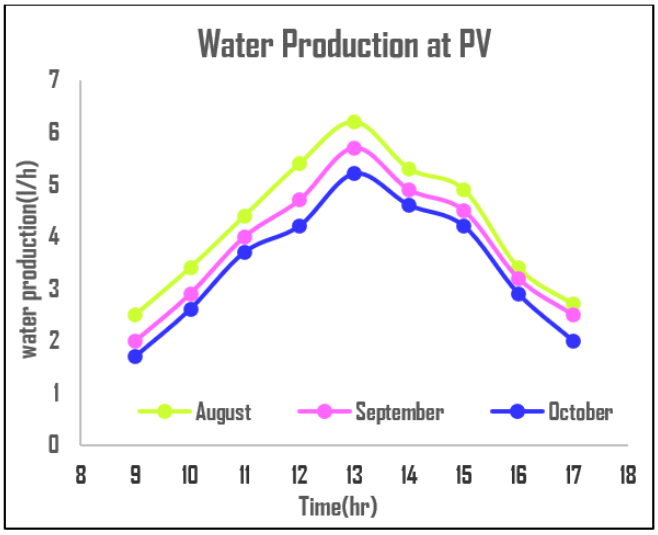

Figure 11. Water production used Photovoltaic (PV) panels

Figure 12 shows the water production of an RO system using photovoltaic panels and national electricity for 8 hours for each month of the test. The figure demonstrates the importance of using a RO system using solar panels instead of national electricity, which is a successful alternative and a suitable clean energy option. The solar-powered RO system combines water desalination efficiency with energy sustainability. Despite some technical and economic challenges, it represents a promising option for future water security, especially in desert and rural areas with strong solar radiation. Figure 13 shows a comparison between the daily water production rate of a photovoltaic (PV)-powered RO system and the national electricity usage for each test month. The figure demonstrates the importance of using a RO system using solar panels instead of national electricity, which is a successful and suitable clean energy option.

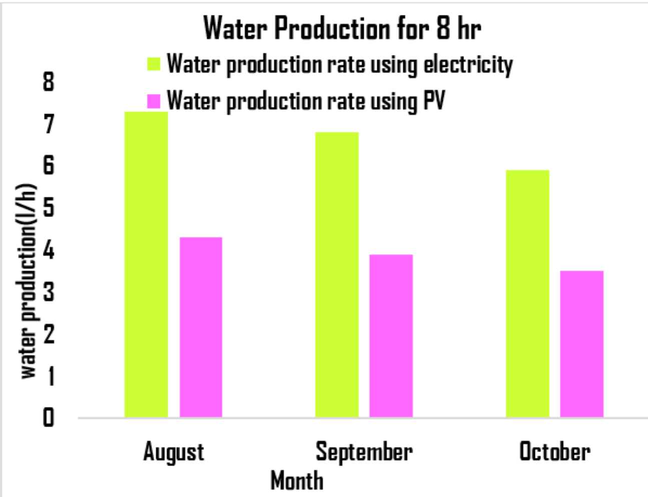

Figure 12. Water production for 8 hr

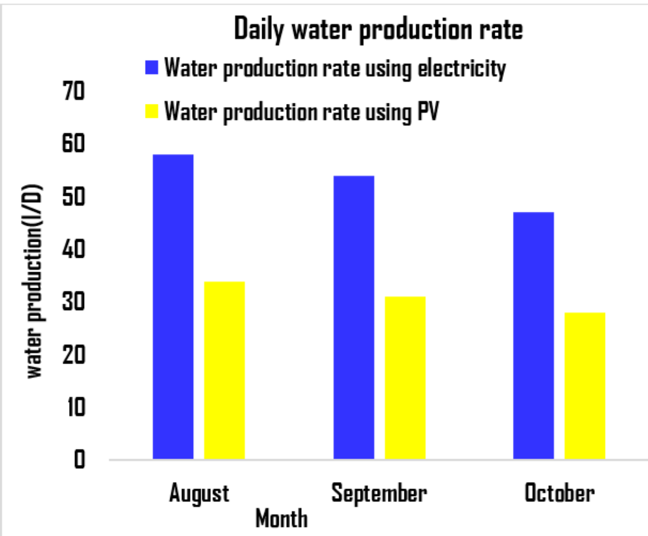

Figure 13. Daily water production rate

5. CONCLUSIONS

In this research, the authors sought to examine the performance of a small-scale sort of solar-powered reverse osmosis (PV-RO) desalination system in Baghdad, Iraq, under climatic environment conditions. The system incorporates PV panels that are combined with RO device in an effort to desalinate the seawater and uses the return water used by the RO system to cool the PV panels.

The experiment results indicate that the cooling system suggested really lowered the panel temperature of the PV collection panels by about 25 ℃ to 5 ℃ and this caused the electrical effectiveness to enhance. The cooling plan enhanced the electric generation of the panels, by about 8.6 percent and enhanced the PV efficiency as 11.8% to 12.58% in August and 10.97% to 11.21% in September and the October PV efficiency was 10.4% to 10.82%.

Also, the PV-RO system was able to generate freshwater under actual conditions of operation with an average production rate of 6.2 L/h in the month of August and 5.1 L/h in the month of October. The findings affirm that solar desalination systems can be used to supply a sustainable and reliable supply of water in a high solar radiating area.

In general, PV-based reverse osmosis systems topped with return-water cooling could be a good solution to enhance the energy efficiency and freshwater extraction in remote and arid areas. Future efforts to work on the cooling design and analyze the sustainability of the system is needed in the future under different environmental conditions.

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