Journal of Engineering Research

Volume 7 | Issue 1 Article 15

2023

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Mohamed Abdelgaied

Journal of Engineering Research (ERJ)
Vol. 7 – No. 1, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Experimental Investigation of the Innovative Small Hybrid Desalination Plant Powered by PVT Panel for Remote Regions

Mohamed Abdelgaied [1,2], Mohamed Fathi Seleem [1], M.M. Bassuoni [1], Ahmed M. Khaira[1]

[1]Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt.

[2]Corresponding author: E-mail address: Mohamed Abdelgaied (mohamed_abdelgaied@f-eng.tanta.edu.eg)

Abstract: **The present study aims to innovate small hybrid desalination plants suitable for remote regions working with higher productivity and lower cost of the produced fresh water. To achieve this idea, the small RO desalination plant was combined with the solar still, as well as this innovative hybrid desalination system was combined with the photovoltaic/thermal panel and the evacuated tube solar collector as preheating units to heat the water before it entered the proposed innovative small hybrid desalination plant. To illustrate the characterized of the proposed innovative small hybrid desalination plant, the performance of an innovative small hybrid desalination plant was compared to the conventional small RO desalination plant experimentally under the climate conditions of Tanta city, Egypt. The results presented that the annual permeate water that can be produced from the conventional small RO desalination plant without modification reached 173.74 m3/year, but for the proposed innovative small hybrid desalination plant the annual permeate water that can be produced will be increased to 352.59 m3/year, with an improvement of 102.94%. Also, the economic analysis presented that the cost of permeate water produced from the *conventional* RO plant without modification reached 0.915 $/m3. But the permeate water cost produced from an innovative small hybrid desalination plant will be reduced to 0.8178 $/m3, saving 10.62%.**

***Keywords*: Innovative hybrid desalination plant, RO desalination system, Solar still; PVT panel, Evacuated tube solar collector.**

I. INTRODUCTION

Although Earth is covered 71% of it with water, about 97.5% of this water is saline water that cannot be directly used as freshwater for everyday usage [1]. According to World Resources Institute (WRI), 12 out of the 17 most water-stressed countries in the world are located in the Middle East and North Africa (MENA) region with baseline water stress levels exceeding 80%. This indeed sounds the alarm to find a reliable source of freshwater. Desalination has shown a great role in affording freshwater from saline water. Many desalination methods were approached and tested for freshwater production like multi-stage flash desalination (MSF) [2-6], Electrodialysis (ED) [7,8], Reverse Osmosis (RO) [9,10], Solar stills [11-13] and other methods.

Reverse Osmosis (RO) desalination is the most common desalination method in the world as it accounts for about 65% of the world's product of desalination freshwater [14]. RO is based on membrane desalination using a membrane that permits only water molecules to flow through and stops salt passage [15]. RO desalination is characterized with high permeate flow rate, high salt rejection that can reach 99%, high packing density, and being cost effective compared to thermal desalination processes. But its disadvantage can be shortened in its high energy requirements [16]. Feed preheating for RO can improve RO performance by increasing water productivity and lowering its Specific Energy Consumption (SEC) due to lowering the water viscosity, but it is limited to a maximum temperature depending on membrane's material [17].

And as the emissions from fossil fuels reached a value of about 90% of global co_2 emissions reported by The Intergovernmental Panel on Climate Change (IPCC) (2022) [26]. While most desalination methods are driven by electrical power, which is mostly produced from burning fossil fuels, the emissions produced due to desalination processes can be treated as a huge disadvantage and not less concerning than the high energy needs. So, it was reasonable to replace those fossil fuels-based electrical powers generating methods with renewable sources to eliminate emissions and climate changes and make desalination friendlier to the environment. Photovoltaic (PV) panels can be used to drive the electrical pumps used to pressurize feed water to the RO membrane. Through this, emissions will be eliminated. The most common RO feed preheating method can be approached by the combination with solar Photovoltaic panels, by cooling the PV panel to improve its efficiency, and the water cooling the PV panel is either used directly to feed the RO membrane or by heat exchanging to water forced to the RO membrane [18,19]. Abdelgaied et al. [20] theoretically studied the impacts of PVT panels and solar dish concentrators on the performance of small RO desalination plants in remote regions. They conducted that the saving in power consumption varied between 24.33-35.79%. Abdelgaied et al. [21] conducted the behavior of an HDH-RO desalination plant powered by PVT panels and solar collectors. Abdelgaied et al. [22] presented the comprehensive modification technology that was conducted on the membrane distillation which aimed to improve the rate of permeate water produced from reverse osmosis desalination systems. Abdelgaied et al. [23] studied the performance of a small hybrid HDH-RO desalination plant powered by a solar dish concentrator and PVT panels for remote regions.

Another way to desalinate water with solar energy is to use solar stills. Solar stills are based on the concept of using solar radiation to evaporate salty water, then water vapor is condensed on a cold surface and the distilled water is then collected through the trough. Solar stills are affected by various parameters like feed water temperature, ambient

DOI: 10.21608/ERJENG.2023.192218.1151

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Vol. 7 – No. 1, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

conditions, water depth, and tilting angle. Feed water preheating to solar stills is very effective in increasing distilled water production as it increases the vapor pressure difference inside the still which increases the water evaporation rate. Preheating the feed of solar still was experimentally tested by Badran and Al-Tahaineh [24], the preheating was achieved by a solar flat plate, and it was found that preheating improved the amount of water accumulated by 36%. Cherraye [25] found that integrating solar still with one flat plate collector increased production by 87%. Abd Elbar and Hassan [26] compared the performance of a solar still without preheating and a similar solar still with feed preheating which was done by cooling a photovoltaic panel surface, the results had shown that preheating the solar still feed water by 60% increase the productivity of the solar still, the energy efficiency, the exergy efficiency by 20.9%, 20%, and 60.64%, respectively. Also, mathematical modeling for the solar still preheated by a PV Thermal panel in this research is proposed by El-Gazar et al. [27] with an error of 3.59% with the experimental results. Al-Molhem and Eltawil [28] performed a cost analysis for both cases solar still without and with preheating, it was found that preheating the feed water lowered the cost per cubic meter from 0.062 to 0.059 $. Faisal et al. [29] studied numerically the heat transfer process in solar stills with preheating; efficiency was improved by 27% referring to the case without preheating. Some studied modification was conducted on the design of the solar distillers which aimed to improve its products such as absorber metal [30-36], fins [37-42], sensible energy storage materials [43-45], and latent energy storage materials [46-55].

This study presents an innovative and effective solution for remote regions that suffer from the problem of water shortage, by creating a small innovative hybrid water desalination plant suitable for remote regions with high productivity and less cost of producing fresh water. To achieve this, the study dealt with presenting an innovative design of a small hybrid water desalination plant suitable for remote regions. To evaluate the performance of innovative small hybrid water desalination plants, performances of innovative small hybrid water desalination plants were compared to conventional RO desalination plants experimentally under the climate conditions of Tanta city, Egypt.

II. EXPERIMENTAL SET-UP

In this system, a PV panel with a cooling system, a solar collector of the evacuated tube type, a single slope solar still, and a RO membrane were merged together to analyze the effect of adding those individual systems to each other to build a system capable to generate energy and produce freshwater. The solar collector was inserted in the system to raise temperature of the water before entering a desalination system. To protect the RO membrane from being damaged, a pretreatment unit consisting of two filters before the pump was used to remove any fouling that can block the RO membrane pores. Also, to protect the membrane from compaction due to high water temperature, cold water was mixed with hot water feed to balance the temperature before entering the membrane. For the solar still, a single slope solar still was tested with preheating performance improvement technique. The idea of adding it to this system is to benefit from the highly concentrated water with high temperature that was rejected by the membrane. The PV panel was cooled by water to improve its efficiency and reduce the heat losses to the ambient from it, also the cooling water for PV was forwarded to the evacuated tube solar collector to gain from its thermal energy and maintain the water level in the solar collector. A drawing of the designed system is illustrated in Figure 1.

The experimental operation of the system was tested at Tanta University, Egypt in the period from 21/7/2022 to 15/8/2022. The operation time was about 8 hours taken from 9:00 am to 5:00 pm throughout the day to measure the performance parameters of the system's components. Temperatures were recorded using a digital temperature sensor connected to an Arduino UNO board with an accuracy of ±0.5°C and a range with a maximum temperature of 125°C. The concentration of salts dissolved in water was recorded by a TDS meter with a range of up to 10000 PPM. A Multimeter was used to measure the voltage and current generated by the photovoltaic panel. The feed and permeate water flow rate was recorded by the utilization of rotameters throughout the operation time. The specification of all measuring devices is presented in Table 1.

Table 1. Specifications of measuring instrumentations

Instrumentations	Range	Accuracy
Temperature Sensor	-10°C to +125°C	± 0.5°C
Flow meters	2 to 18 l/min	± 4 %
TDS meter	0.0-10,000 ppm	± 2%
Pressure gauge	0.0 to 10 bar	± 2.5 %

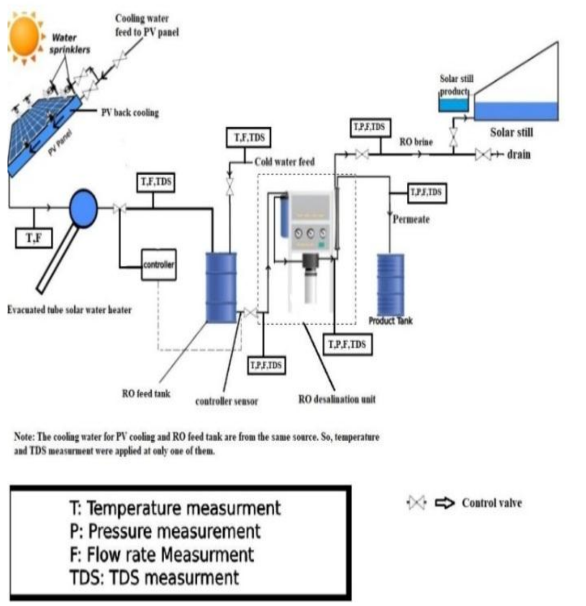

Fig. 1. A drawing of the suggested hybrid system

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Vol. 7 – No. 1, 2023
©Tanta University, Faculty of Engineering
https://erjeng.journals.ekb.eg/
ISSN: 2356-9441 e ISSN: 2735-4873

The uncertainty of calculated results is estimated using equation (1) [56]:

$$W_R = \sqrt{\left(\frac{\partial R}{\partial X_1} W_1\right)^2 + \left(\frac{\partial R}{\partial X_2} W_2\right)^2 + \left(\frac{\partial R}{\partial X_3} W_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n} W_n\right)^2} \quad (1)$$

where; W_1, W_2, W_3, …, W_n are the uncertainties of independent variables. The calculated uncertainty of the permeate water productivity is ±1.93 %.

III. RESULTS AND DISCUSSION

Experimentally to assess the performance of a small hybrid desalination plant, the practical studies were conducted at the Faculty of Engineering, Tanta University, Egypt, in July and August 2022. The experimental data were recorded from 9:00 am to 5:00 pm. Fig. 2 shows the experimentally recorded data of solar rays intensity, the temperature of feed water entering the RO desalination unit, solar still basin water temperature, solar still glass temperature, and ambient air temperature. As shown, the recorded solar ray's at 9:00 am reached 530 W/m^2 and continuous increase until reached 1045 W/m^2 at midday, after that the intensity of solar rays decreases continuously until reached 290 W/m^2 at 5:00 pm. During the test period, the temperature of the water entering the RO unit remained constant at 42 ºC. For the solar still, the basin water temperature increased gradually from 52 ºC at 9:00 am to 77 ºC at 1:00 pm, and after that gradually decrease unit reached 58 ºC at 5:00 pm. Also, the solar still glass temperature varies between 41-50 ºC and the ambient air temperature varies between 37-42 ºC.

Figure 3 shows a comparative study of the hourly permeate water productivity of a conventional small RO desalination plant without modification and the proposed innovative small hybrid desalination plant. As shown in Fig. 3, the hourly permeate water productivity of a conventional small RO desalination plant without modification reached 68 liter/hr. But for the proposed innovative small hybrid desalination plant incorporating the PVT panel and evacuated tube solar collector as preheating units, the hourly permeate water productivity will be increased to 137 liter/hr.

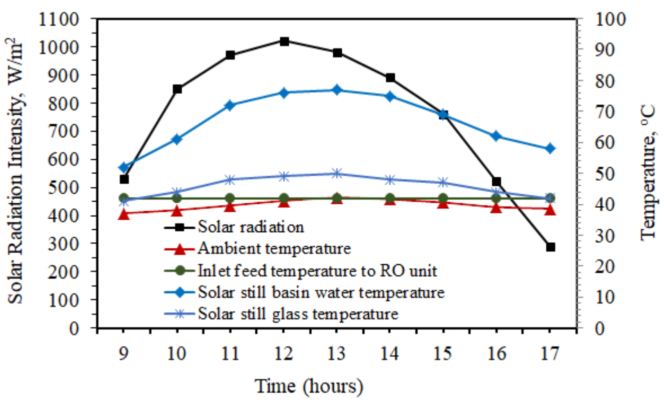

Fig. 2. Variations of solar ray's intensity and the temperatures of feed water entering the RO unit, basin water, glass, and ambient air

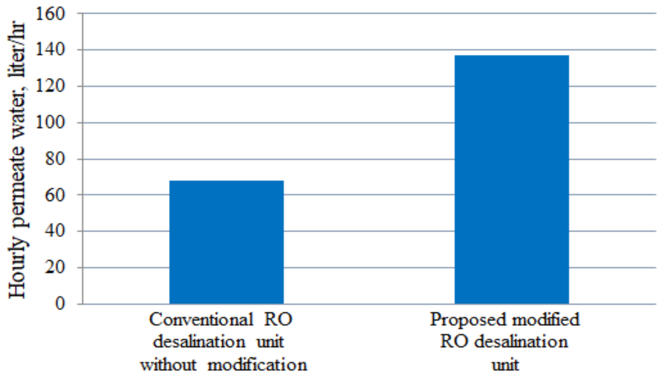

Fig. 3. Hourly permeates water productivity of a conventional RO plant without modification and the proposed innovative small hybrid desalination plant.

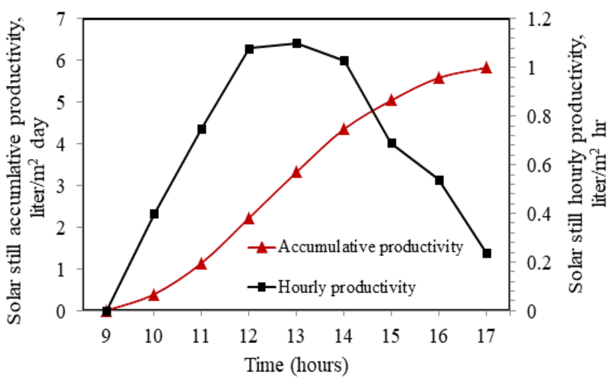

Fig. 4. Hourly and accumulative distillate water productivity of solar still during the test periods from 9:00 am and 5:00 pm.

These are mainly because of the increase in the permeate water across the membrane with increases in the feed water temperature due to the reduction in the water viscosity. Figure 4 shows the hourly and accumulative distillate water productivity during the test periods from 9:00 am and 5:00 pm. As shown in Fig. 4, the maximum hourly distillate water productivity reached 1.1 liter/m^2 hr at 1:00 pm. Also, the accumulative distillate water productivity reached 5.83 liter/m^2 per day.

To illustrate the characteristics of utilizing the proposed innovative small hybrid desalination plant for remote regions, Fig. 5 shows a comparative study of the annual permeate water that can be produced from the conventional small RO desalination plant without modification and the proposed innovative small hybrid desalination plant. As shown in Fig. 5, the annual permeate water that can be produced from the conventional small RO desalination plant without modification reached 173.74 m^3 per year, but for innovative small hybrid desalination plant the annual permeate water that can be produced will be increased to 352.59 m^3 per year.

These results presented that using of innovative small hybrid desalination plant to produce freshwater for remote regions represents a good choice, which improves the freshwater productivity by 102.94% as compared to conventional small RO desalination plants without modification.

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https://erjeng.journals.ekb.eg/
ISSN: 2356-9441 e ISSN: 2735-4873

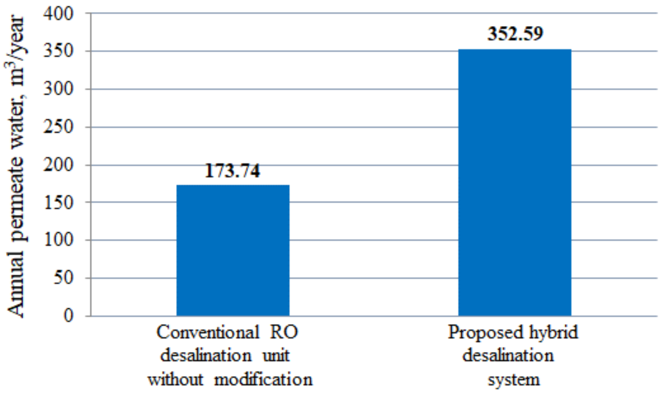

Fig. 5. Annual permeates water produced from a conventional RO plant without modification and the proposed innovative small hybrid desalination plant.

IV. ECONOMIC ANALYSIS

The economic analysis in this experimental study aims to demonstrate the economic feasibility of innovative small hybrid desalination plants in remote regions. The economic feasibility study was done using the procedure presented by Kabeel and Abdelgaied [31]. The capital cost of the conventional RO plant without modification and the proposed innovative small hybrid desalination plant are shown in Table 1. Also, Table 2 shows the cost details of a conventional RO plant without modification and the proposed innovative small hybrid desalination plant. As shown in Table 2 and Fig. 6, the economic analysis presented that the cost of permeate water produced from the conventional RO plant without modification reached 0.915 $\$/m^3$. But the permeate water cost of an innovative small hybrid desalination plant will be reduced to 0.8178 $\$/m^3$. The economic feasibility demonstrated that using the innovative small hybrid desalination plant reduced the cost of permeate water by 10.62% as compared to the conventional RO plant without modification.

Table 1. Capital cost of proposed system

Unit component	Conventional RO desalination unit without modification	Proposed hybrid desalination system
RO Unit	22000 LE	22000 LE
Solar Water Heater	-	21000 LE
PV Panel	-	1000 LE
Thermostat	175 LE	175 LE
Circulating Pump	240 LE	240 LE
Tanks	200 LE	200 LE
Solar Still	-	610 LE
Valves and fittings	-	500 LE
Total capital cost, LE	23015	45725

Table 2. Cost details of the proposed system

Cost (LE)	Conventional RO desalination unit without modification	Proposed hybrid desalination system
Capital cost (CC)	23015	45725
Interest(I)	0.15	0.15
Lifetime of system (n) years	20	20
Capital recovery factor(CRF)	0.1598	0.1598
Annual capital cost (ACC)	3676.9	7305.1
The annual maintenance cost (AMC)	661.84	1314.92
Salvage value (SV= 20% CC)	4603	9145
Sinking fund factor (SFF).	0.00976	0.00976
annual salvage (AS) = SV x SFF	44.932	89.269
Annual total cost (ATC) (LE/year)	4811.365	8722.491
Annual permeate of RO (L/year)	173740	350035
Annual permeate of solar still (L/year)	0	2555
Total annual permeate (L/year)	173740	352590
Cost of liter (LE/liter)	0.0277	0.0247
Cost of liter (LE/m^3)	27.69	24.74
Cost of liter ($\$/m^3$)	0.915	0.8178

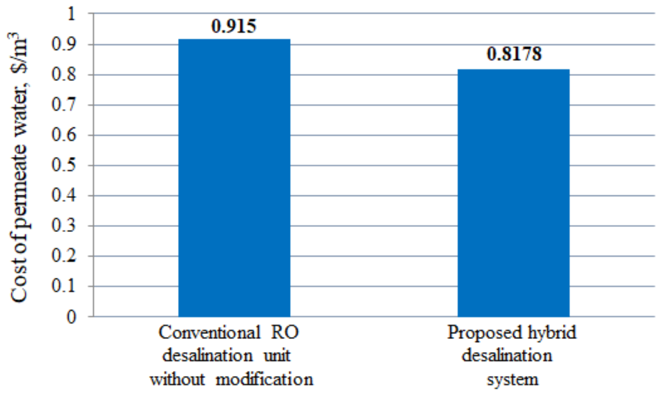

Fig. 6. Cost of permeates water produced from a conventional RO plant without modification and the proposed innovative small hybrid desalination plant.

V. CONCLUSIONS

The experimental work aims to innovative and effective solutions for remote regions that suffer from the problem of water shortage, by creating a small innovative hybrid water desalination plant suitable for remote regions with high productivity and less cost of producing fresh water. To achieve this, the study dealt with presenting an innovative design of a small hybrid water desalination plant suitable for remote regions. To evaluate the performance of this innovative small hybrid water desalination plant, the performances of the proposed innovative small hybrid water desalination plant were compared to conventional RO desalination plants experimentally under the climate conditions of Tanta city, Egypt. The main results are as follows:

- The annual permeate water that can be produced from the conventional small RO desalination plant without modification reached 173.74 m^3/year, but for the proposed innovative small hybrid desalination plant the

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annual permeate water that can be produced will be increased to 352.59 m^3/year, with an improvement of 102.94%.

- The economic analysis presented that the cost of permeate water produced from the conventional RO plant without modification reached 0.915 \$/m^3. But the permeate water cost of an innovative small hybrid desalination plant will be reduced to 0.8178 \$/m^3.
- The economic feasibility demonstrated that using the innovative small hybrid desalination plant reduced the cost of permeate water by 10.62% as compared to the conventional RO plant without modification.

Funding: This research did not receive any type of grant from funding agencies, either public or private sectors, commercial, or not profit sectors.

Conflicts of Interest: There are no ethical issues applied to this research and no conflict of interest.

NOMENCLATURE

ACC	Annual Capital Cost, LE
AMC	Annual Maintenance Cost, LE
AS	Annual Salvage, LE
ATC	Annual Total Cost, LE
CC	Capital Cost, LE
CRF	Capital Recovery Factor, -
I	Interest, %
n	Lifetime of System, year
SEC	Specific Energy Consumption, kWh/m^3
SFF	Sinking Fund Factor, -
SV	Salvage Value, LE

ABBREVIATIONS

ED	Electrodialysis
MENA	Middle East and North Africa
MSF	Multi-Stage Flash Desalination
PCM	Phase Change Materials
PV	Photovoltaic Panel
PVT	Photovoltaic/Thermal Panel
RO	Reverse Osmosis
WRI	World Resources Institute

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DOI: 10.21608/ERJENG.2023.192218.1151