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Investigation of hybrid solar-driven desalination system employing reverse osmosis process

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ABSTRACT

The water resources are depleting rapidly due to the increasing population of the world. Thus, it has become a big challenge to provide sustainable quality water for future generations. Unfortunately, due to decreasing rivers/canals water supply, the trend of groundwater pumping has increased for agricultural purposes during the last few decades especially in developing countries of Africa and Asia like Pakistan. The freshwater-scarce areas in the world are now relying on water desalination processes. In the recent era, the desalination has emerged as a potential method to produce freshwater. Although the process of desalination is an acceptable way to convert saline to freshwater, this is a highly electrical energy-intensive process. At the same time, the availability of enormous daily solar energy in many parts of the world provides an excellent opportunity to operate reverse osmosis (RO) systems. The hybrid solar system seems to be a feasible solution for continuous water desalination throughout the day. Thus, this study was carried out for the development and experimental investigation of a 500 L h^{-1} decentralized photovoltaic (PV-RO) system. Based on the running load of the RO system, a 2 kW$_p$ PV system was coupled with RO plant through 5 kVA hybrid inverter. The experiments were conducted in terms of no tracking and three-point manual PV tracking, cooling, and no-cooling of the PV system. The results showed 18% higher daily PV energy using PV tracking and 10% higher PV energy by cooling of PV panels. The sizing and development process of this system is helpful for easier selection and installation of a decentralized hybrid PV-RO system to perform environmental friendly desalination of water by the community to meet the future challenges of water scarcity.

Keywords: Saline water; Carbon emissions; Desalination; Reverse osmosis; Hybrid solar system

1. Introduction

The freshwater scarcity issues are increasing day by day especially in developing countries of the world. It is estimated that 1.1 billion population in the world have inadequate access to quality freshwater for drinking purpose. The increasing world population, urbanization and industrial expansion have increased the freshwater demand throughout the world. In Pakistan, the Sindh and Balochistan Provinces are facing sever issues of freshwater supply. According to the United Nations World Water Development (UNWWD) report, the water demand has increased from 2,961 to 3,420 m^3 cap^{-1} from the

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year 2000–2005 respectively. Similarly, according to Pakistan Water Partnership the available ground and surface water reserves were 24 and 153 million acre feet respectively. According to the United Nations Educational, Scientific and Cultural Organization report, the available water supply in Pakistan is slightly above 1,000 m^3 per capita thus lying it in the list of water stress countries [1]. The P&D Division of Government of Punjab also reported that per capita water availability in Pakistan has declined from 1,299 to 1,101 m^3 from 1996–1997 to 2004–2005 respectively. The current situation is more worsened due to the rapidly increasing population, urbanization, and industrial expansion. It is estimated that the population of Pakistan will be doubled during the next 25 years which will further decrease per capita availability of water. According to an estimate, about 36% of groundwater in Pakistan is considered as saline water. Moreover, due to decreasing rivers/canal's water supply, the trend of groundwater pumping has increased for agricultural purposes. In Pakistan, the annual growth rate of diesel and electric driven tube wells was 6.7% and 7.4%, respectively.

The world areas facing freshwater scarcity are now relying on water desalination processes. In the recent era, desalination is a novel method to produce abundant fresh water supply. Although desalination is an acceptable way to convert saline to freshwater, this is a highly electrical energy-intensive process. To produce 1,000 $m^3\ d^{-1}$ desalinate through thermal desalination (TD) requires 10,000 ton y^{-1} of crude oil [2]. Therefore, under these circumstances, it is dire need of the time to replace conventional thermal and electrical energy with an environment-friendly electrical energy source to produce fresh water through the desalination process. The solar-driven reverse osmosis (RO) plants can play a vital role to eliminate heavy dependence on fossil fuels and conventional electrical energy making it a sustainable energy source producing adequate freshwater [3].

Abdelkareem et al. [4] studied desalination processes driven by solar, wind and geothermal energy. It was also found that the efficiency of the off-grid photovoltaic (PV) system is strongly linked with the successful designing and arrangement of PV arrays, providing solar tracking, adjustment of tilt angle and cleaning methods. The cooling of the PV system also enhanced PV efficiency as well as distillate production thus decreasing overall water production cost. Ali et al. [5] studied the innovative combination between RO and adsorption desalination (AD) system along with simulations using MATLAB. The AD was operated using low temperature solar thermal heating source. The results showed that this combination increased the recovery rate by gradually decreasing permeate salinity. Charcosset [6] reported that the membrane processes include RO, electrodialysis and membrane distillation. These systems were coupled with renewable energy technologies such as solar, wind and wave energy. The authors also reported working principles, plant design, mathematical models and economic feasibility. The authors concluded that PV driven RO plants were most efficient in terms of energy consumption and suitable for small scale users.

Ahmad and Schmid [7] carried out a feasibility study of brackish water desalination in the Egyptian desert employing solar PV systems. Gocht et al. [8] studied the PV-RO system for desalination in Jorden while Richards and Schäfer [9] tested solar-driven desalination in Australia for remote communities. Tzen et al. [10], Kalogirou [11], and Bouguecha et al. [12] also evaluated solar PV driven RO systems for brackish water desalination. Goosen et al. [13] reviewed recent trends and challenges in renewable energy-driven desalination systems.

He et al. [14] reported that PV-RO pressure retarded osmosis (PV-RO-PRO) plant was developed considering hourly solar data of Perth, Australia. The authors found that annual production was increased more than nine times using PV-RO-PRO as compared to conventional RO system. Liu et al. [15] recommended the use of energy recovery devices to decrease energy consumption to improve the energetic efficiency of the system. The authors carried out an exergy-based analysis of dual-stage nano-filtration seawater desalination. The energetic and exergetic analyses were performed to calculate the losses in the system. The results showed that the major portion of exergy destruction was observed in the membrane section and steam valves. Shalaby [16] conducted a study on RO desalination run by PV and solar-based Rankine cycle. The battery-less PV system was recommended to operate the RO plant to reduce capital investment and replacement costs. In the case of a solar-based Rankine cycle, it was concluded that the use of energy recovery devices eliminates water preheating. It was also recommended that the use of toluene in the organic Rankine cycle (ORC) achieved a maximum temperature of 380°C while condensation temperatures of 35°C. The cost of solar-based ORC was also reduced to 30% after its commercialization. Dimitriou et al. [17] developed a mathematical model to study mass-transfer through membrane under non-constant operating conditions of a spiral wound RO membrane module. The performance of the membrane under varied operational conditions were also carried out. The results showed that in the case of physical membrane contraction under non-constant operating conditions, the water flux drop of 0.2×10^{-3} kg $m^{-2}\ s^{-1}$ was observed due to sudden grow in applied pressure. Wilf and Klinko [18] and Wilf and Bartels [19] also carried out optimal designing of seas water RO desalination. Ghermandi and Messalem [20] reported that PV-RO as mature technology with unit cost as low as 2–3 US$ m^{-3}.

Pakistan being an energy deficit country direly needs to rely on solar-based desalination to address the issues of water scarcity in the country. Luckily, Pakistan lies on a sunny belt with irradiation ranged 5–7 kWh $m^{-2}\ d^{-1}$ and sunshine hours of 1,500–3,000 [21]. In recent years, the desalination markets have grown rapidly throughout the world and a further increase is also expected in future.

The RO technology is surpassing TD in terms of its market shares and demand [22]. PV-RO process is an innovative idea to convert brackish water into fresh water because the RO membrane can remove 98%–99.5% salts from feed water [23]. The optimum pressure for brackish and seawater lies between 10–15 and 55–65 bar respectively for normal operation of the RO system [22]. Eke and Senturk [24] in a study carried out in Turkey resulted that about 30% of energy can be increased employing solar trackers with PV as compared with a fixed solar PV system. Dakkak and Babelli [25] also found that 30% of energy was increased by employing a tracking system with a solar PV system. Huang and Sun [26] concluded that up to 56% increased power output can be achieved using a one-axis three-position tracking system. Bentaher et al. [27] also encouraged tracking of the PV system to harness maximum energy during the daytime.

In Pakistan, the water scarcity issues are increasing especially in Southern Punjab, interior Sindh, Balochistan, and remote coastal areas. Due to the drinking of poor quality water, the issue of water-borne diseases is increasing in these areas. Moreover, the industrial wastes have also contaminated the groundwater reserves with heavy metals such as cobalt, nickel, copper causing different diseases such as hepatitis and stomach problems. The Pakistan Council for Research and Water Resources (PCRWR) has alarmed that rapid groundwater depletion can result in drought-like situation in major cities of Pakistan. Thus, it is high time to tackle this issue on war footings. Realizing the situation, the Chief Justice and Prime Minister of Pakistan has initiated a campaign to construct Diamer Basha and Mohmand Dam.

Keeping in view the above scenario, this study was carried out for investigation of a hybrid solar-driven desalination system employing the RO process under temperate climatic conditions. The system was evaluated in terms of no-tracking and three-point manual PV tracking, cooling and no-cooling of PV system and water quality analysis before and after RO desalination.

2. Material and methods

The study was carried out for the development, installation and performance evaluation of PV-RO plant to promote sustainability in energy generation and water productivity. A hybrid solar operated RO plant having a capacity of 0.5 $m^3 h^{-1}$ has been developed and installed in the Workshop of Department of Farm Machinery and Power, University of Agriculture, Faisalabad, Pakistan. The preliminary PV-RO design was carried out using Solidworks software as shown in Fig. 1. After design verification, the energy required to run a 0.5 $m^3 h^{-1}$ plant was measured to determine the running load of the system for the sizing of the PV system.

2.1. Sizing of the PV system

The design of a solar PV system is based on the running load of the RO system. The current of single-phase low and high-pressure pumps was measured using a multimeter to calculate the power required to run the RO plant. Based on measured current, the running load of RO plant was calculated to be 1,600 W while the intermittent load was found to be 3,080 W. It is worth mentioning here that, in order to reduce capital investment and size of PV system,

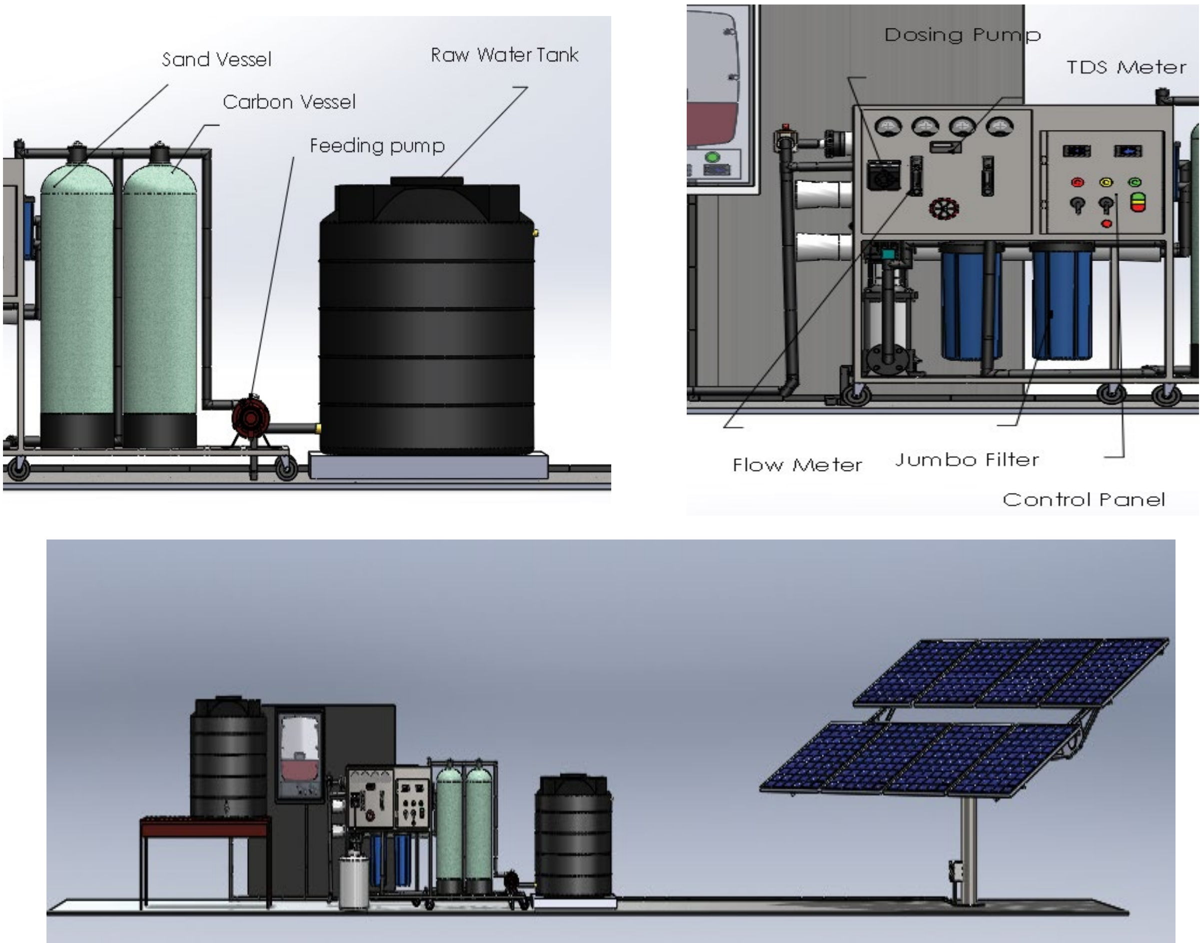

Fig. 1. Isometric views of the PV-RO system.

a hybrid inverter was used to meet intermittent/torque load of RO plant using grid electricity. The hybrid inverter will also ensure the continuous working of the RO plant in case of adverse climatic conditions. The procedure for sizing of PV system is given below:

Running load of RO pumps, P_{motors} = 1,600 W
PV array design factor, F_{PV} = 1.35
PV array size based on motor power, $P_{PV} = P_{motors} \times F_{PV}$ = 2,160 W
Peak power of a module = 270 W_p
No. of PV modules required, $N_{PV} = P_{PV}/270$ = 8.0
Required capacity of off-grid inverter (as per torque load) = 5,000 W (maximum up to 10,000 W).
No. of strings calculated using excel software, N_{string} = 01.
Open circuit voltage (input direct current (DC) volt per string at standard temperature conditions (STC),, $V_{oc} = N_{PV} \times V_{oc} = 8 \times 38.8 = 310$ V
Maximum power voltage (DC volt) per string on STC, $V_{mp} = N_{PV} \times V_{mp} = 8 \times 31.7 = 254$ V
Total current per string, I_{total} = 8.67 Amp

The V_{oc} (DC volt) per string at STC is less than the maximum input direct current voltage (VDC) of the inverter, that is, 310 VDC < 500 VDC, so the design is OK.

The V_{mp} (DC volt) per string on STC is within the range of maximum power point tracking voltage range of the inverter, that is, 254 VDC is within the range of 120~450 VDC, so the design is OK.

The specifications of the PV system and off-grid inverter are shown in Table 1.

A three-point manual tracking structure is used for the mounting of PV modules. The PV modules are connected in

Table 1
Specifications of PV module and off-grid inverter

Items	Specifications
Cell type	Polycrystalline silicon with 60 cells per module
Module type	JKM270PP
Maximum power at STC, P_{max}	270 W_p
Maximum power at NOCT	202 W_p
Module efficiency at STC	16.50%
Maximum power voltage at STC, V_{mp}	31.7 V
Maximum power current at STC, I_{mp}	8.52 A
Open circuit voltage at STC, V_{oc}	38.8 V
Short circuit current at STC, I_{sc}	9.09 A
Maximum system voltage	1,000 VDC
Operating temperature	–40°C to +85°C
Maximum series fuse rating	15 A
Nominal operating cell temperature (NOCT)	45°C ± 2°C
DC cable	Single conductor type 99.99% copper, cross-sectional area 6 mm^2 with 1,000 V/class II. Temperature range –40°C to 90°C
Type of inverter	Axpert VM III-500–48 Off-grid inverter with detachable liquid crystal display control module
Rated power	5 kW
Input voltage	230 alternate current voltage (VAC)
Frequency range	50 Hz/60 Hz (auto-sensing)
Output voltage	230 VAC ± 5%
Surge power	10 kVA
Efficiency	90%–93%
Solar charger type	Maximum power point tracking (MPPT)
Maximum PV array power	4 kW
MPPT voltage range @ operating voltage	120–450 VDC
Maximum PV array voltage	500 VDC
Maximum solar charge current	80 A
Maximum alternating current (AC) charge current	60 A

Note: STC refers irradiance = 1,000 W m^{-2}, cell temperature = 25°C, air mass (AM) = 1.5 while NOCT refers irradiance = 1,000 W m^{-2}, ambient temperature = 20°C, AM = 1.5, and wind speed = 1 m s^{-1}.

a series configuration (one string) to make it a single-phase electric supply source. A provision is provided for three-point manual tracking of the PV system to increase daily energy output. Manual tracking is used to reduce system costs in comparison to automatic PV tracking.

The technical specifications of the PV mounting structure are shown in Table 2 while the installation process and actual view of an installed PV system are shown in Fig. 2.

2.2. Description and installation of RO system

The major components of RO plant consist of (1) saline water storage tank (500 L) installed on feed water supply line to remove impurities from saline water through flocculation and coagulation processes, for example, using chemicals such as lime and alum, (2) high and low-pressure pumps, (3) pretreatment cartridges, (4) pressure vessels and housings (carbon and sand vessel), (5) semipermeable membrane, (6) jumbo and small size filters with housings, (7) ultrafiltration membrane, (8) production tank, (9) skids, (10) pressure gauges, (11) flow meter, (12) valves, (13) control panel, and (14) stainless-steel frame and body of the plant as shown in layout diagram in Fig. 3.

The carbon vessel (0.34 m diameter and 1.09 m length) consists of 40 kg carbon and gravel to remove organic contaminants and disinfection from raw water. The sand vessel (0.34 m diameter and 1.09 m length) consists of 40 kg of sand and gravel to reduce bacteria and remove solid particles during water purification. The carbon and sand vessels are backwashed daily to remove water/air. The pre-treatment filters namely activated carbon filter, cartridge filter and block carbon filter were also installed on the feed water supply line to remove bacteria and major contaminants from feed water. The semipermeable membrane is an important part of the RO plant and is used to remove salts from brackish water. Two locally available semipermeable membranes are installed in this RO plant. The diameter and length of each membrane is 0.12 and 1.3 m. The pre-treatment filters help to reduce microbial growth in the RO membrane, thus increasing the life of the membrane. To accomplish the high-pressure

Table 2
Technical specifications of PV mounting structure

Items	Specifications
Civil work	1:2:4 concrete mixtures, base 5 ft × 5 ft × 1 ft, concrete block 3 ft × 3 ft × 5 ft, single-pole having capacity to bear 3.4 kW or maximum, 10 modules per pole.
Type and material	Ground-mounted pole with manual tracking. Capable of seasonal and daily variations. 100 microns hot dipped galvanization for mounting structure. All nuts and bolts are of stainless steel.
Reinforcement cage in civil work	4-J bolts having 0.875-inch rod thickness with 72-inch height. The 5 rings of 0.375-inch at 12-inch × 12-inch center to center distance.
Base plate	16 mm thick and 15 ft × 15 ft base plate.
Main pole	Outer diameter 5.5 ft with a total height of 5 ft. A 6 mm thick flange with 8 holes at 4 ft height from base plate with 8 mm groove for balls in the groove for tracking purpose.
Top structure	*T*-frame/middle pipe diameter of 4 ft with 3 mm thickness. 78 in and 82 in lengths with 2 angle adjusters of 3 holes. Sidearms 2 in × 2 in × 5 mm of 13 ft length with horizontal pipe beams. Angle for PV adjustment 2 in × 2 in × 5 mm.
Grounding and earthing	PV systems and structures are properly grounded for the safety of the system and operators.

Fig. 2. Installation process and actual view of installed PV system.

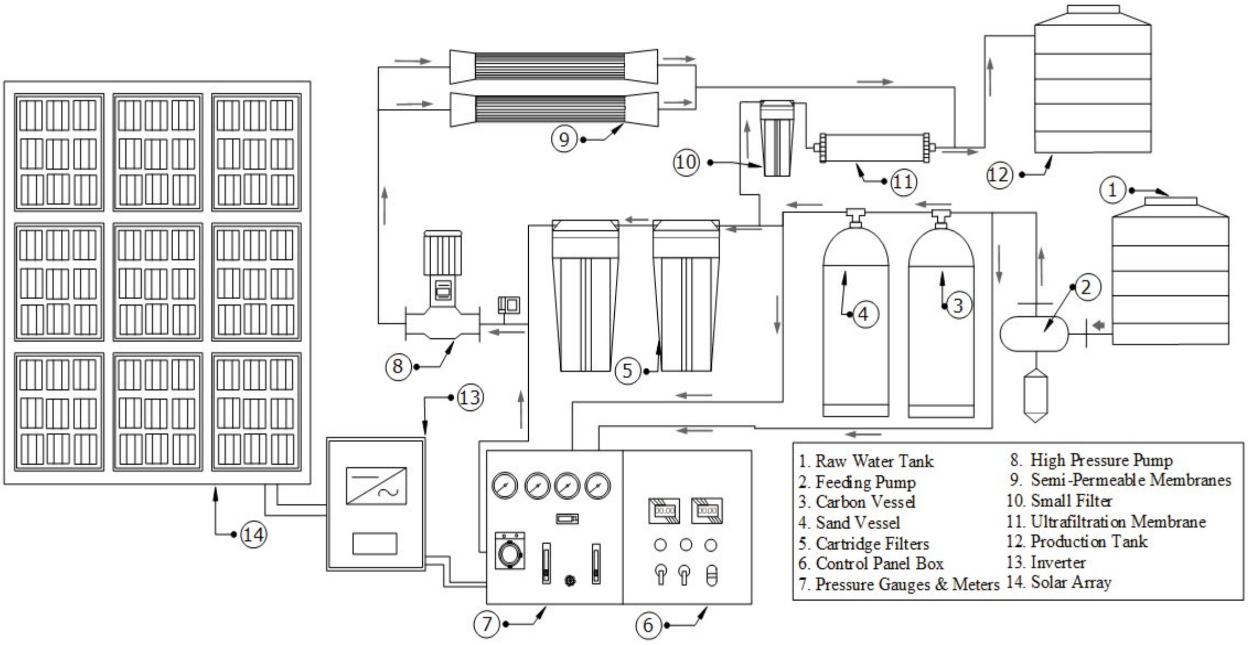

Fig. 3. Layout diagram of the PV-RO system.

requirement of membrane, a high-pressure pump is used. A high-pressure pump increases water pressure up to 100 psi to pass it through membranes. A low-pressure pump is used to accelerate the feed water before the pre-treatment unit. The dosing pump is used for the dosing of anti-scale chemicals to avoid precipitation of salts in the membrane. The anti-scale chemicals are stored in small dosing tank. The post-treatment of water using chlorination may be needed based on the required quality of permeate. For this purpose, an ultrafiltration membrane has also been installed to remove high molecular weight salts before drinking the water. A 500 L production tank is used to store distilled water after the desalination process. The system has been equipped with flow valves, flow pipes, pressure gauges, flow meter, electrical control panel, and wiring accessories. The specifications of the RO system are shown in Table 3 while the actual view of the installed RO plant is shown in Fig. 4.

Table 3
Specifications of RO plant

Items	Specifications
Jumbo type filter	4.5″ × 20″
Small filter	10″
Semipermeable membrane	2 No.
Ultrafiltration membrane	HM90 Model 40–40
Carbon vessels (carbon + gravel)	Capacity 40 kg
Sand vessel (sand + gravel)	Capacity 40 kg
Raw water storage tank	Capacity 500 L
Feeding pump	50 Hz, 80 psi
High pressure pump	50 Hz, 100 psi
Production tank	Capacity 500 L
Anti-scale chemicals	As per requirement

2.3. Performance evaluation of PV-RO system

The experimental study was carried out to study the effect of manual tracking and no-tracking, cooling and no-cooling of the PV system on energy production. The water quality analysis before and after desalination was performed

Fig. 4. Actual view of installed RO plant and hybrid direct current-alternating current (DC-AC) inverter.

to measure total dissolved solids (TDS), hardness, Na, Mg, Ca, and Cl.

3. Results and discussion

The experiments were conducted with tracking (manual) and no-tracking (south-facing), cooling and no-cooling of PV panels during different months of the year to assess the performance of hybrid PV-RO system in terms of energy produced and quality of distillate production. The data was collected from 09:00 am to 05:00 pm throughout the day for clear sky days. The measured parameters include ambient temperature, solar radiation, PV surface temperature, solar and Water and Power Development Authority (WAPDA) current and voltage.

3.1. Effect of tracking and no-tracking of PV system on PV power

The effect of tracking and no-tracking of PV system measured on January 07, 2019 without cooling of PV panels is shown in Fig. 5. The figure shows that the PV power continuously increases by tracking of PV system from 09:00 am to 05:00 pm. After 03:00 pm, the PV power difference was lower due to the tree shadow effect on the PV system due to track as compared to no-tracking (south-facing) of the PV system. The maximum PV power was found to be 1,451 W at 01:00 pm due to the tracking of the PV system. The daily PV energy was found to be 9.2 kWh with no-tracking while 11.0 kWh with tracking of PV system. It shows that 2 kWh (18%) higher PV energy was obtained throughout the day using tracking of PV system under local climatic conditions.

The trend of PV power produced during different days of the months due to tracking of a PV system is shown in Fig. 6 without the cooling of the PV system. The figure shows that PV power produced increased from winter (December) to the summer season (June). The variation in PV power during the evening time is due to the partial shadow effect of trees and nearby buildings on PV panels.

3.2. Effect of cooling and no-cooling of PV system on PV power

The effect of cooling and no-cooling of the PV system on May 13, 2019, without tracking of PV panels is shown in Fig. 7. The figure shows that higher PV power was found due to cooling compared to the no-cooling of PV panels. The maximum power was 1.40 kW at 12:10 pm due to the cooling of the PV system. The heat losses and cell temperature decrease due to the cooling of the PV system thus improving PV power. The total PV energy was measured to be 9.5 kWh with cooling and no-tracking of PV system while it was 8.5 kWh with no-cooling and no-tracking of PV panels. The figure shows that 1 kWh (10%) higher PV energy was obtained due to cooling of PV panels as compared to no-cooling.

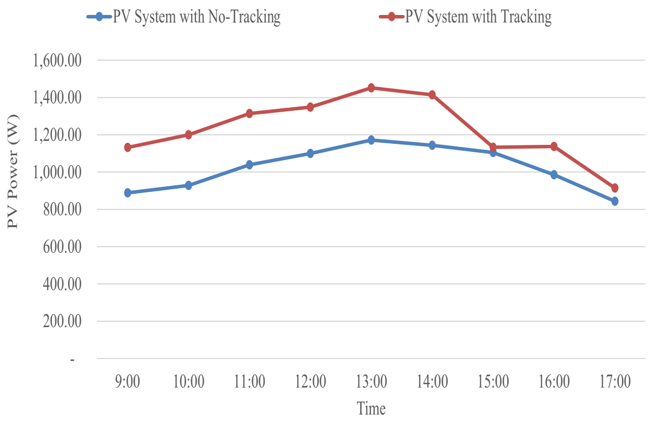

Fig. 5. Effect of tracking and no-tracking of the PV system on PV power without cooling of the PV system.

3.3. Effect of ambient temperature and solar radiation on cell temperature

The effect of ambient temperature and solar radiation on cell temperature during days of the different months is shown in Fig. 8 without cooling and tracking of the PV system. The figure shows the significance of cell temperature differences during December and June. This shows that the cooling of the PV system in summer has the potential to increase PV power significantly. The maximum cell temperature was found to be 51.1°C at 2 pm on June 11, 2019, while December has cell temperature between 20°C and 26°C thus requiring no cooling of PV panels.

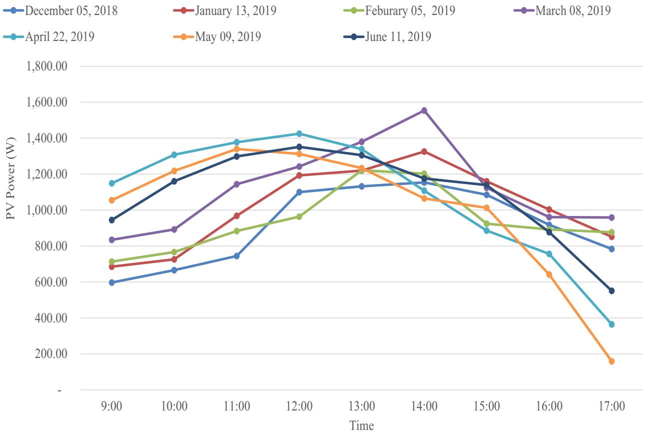

Fig. 6. Effect of PV tracking on PV power during different months.

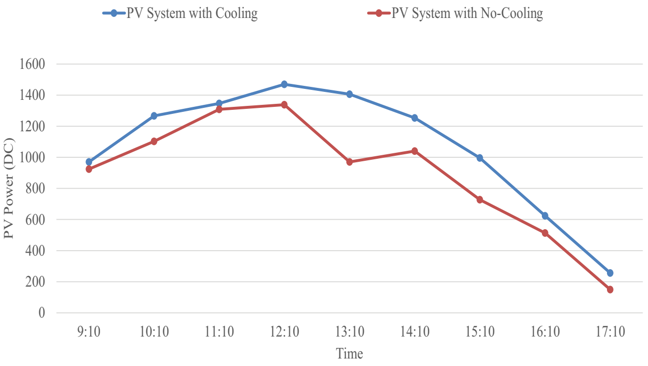

Fig. 7. Effect of cooling and no-cooling of PV system on PV power.

3.4. Energy analysis during hybrid PV-RO operation

The share of PV and WAPDA (grid) power utilization during the working of the RO plant is shown in Fig. 9. The figure shows that the contribution of grid energy was higher in the morning and evening times to maintain the constant load requirement of the RO system. The contribution of solar power increases during noon time due to high solar radiation.

The water quality analysis of water before RO and after RO during different days is shown in Table 4. The table shows that the TDS level was decreased from 1,750 to below 1,000 mg L^{-1} after RO operation. The value of TDS, hardness, Na, Mg, Ca, and Cl was found within the acceptable limit of international water quality standards for drinking purposes.

4. Conclusion

The decreasing natural water reserves due to the increasing population are producing alarming condition for future generations. To maintain the per capita availability of freshwater supply, desalination needs to be carried out at a larger instant shortly. Due to the energy-intensive nature of the desalination process, it will become difficult to perform the desalination process using conventional energy supply. Luckily, the availability of solar energy if utilized effectively can play a vital role to decrease the operational cost of desalinating production. Thus, this study was conducted for the development and testing of a decentralized hybrid PV–RO system. To operate 500 L h^{-1} RO plant, an optimal

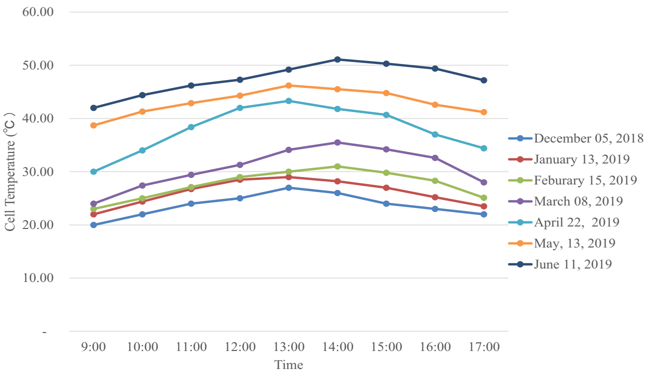

Fig. 8. Effect of ambient temperature and solar radiation on cell temperature.

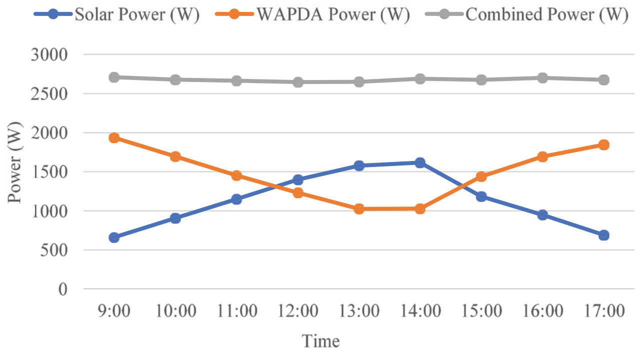

Fig. 9. PV and grid power during the working of the RO plant.

Table 4
Water quality tests before and after RO operation

Date	Before RO						After RO					
	TDS (mg L^{-1})	Hardness (mg L^{-1})	Na (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	Cl (mg L^{-1})	TDS (mg L^{-1})	Hardness (mg L^{-1})	Na (mg L^{-1})	Mg (mg L^{-1})	Ca (mg L^{-1})	Cl (mg L^{-1})
19/4/2019	1,760	220	260	42	22	400	570	248	140	22	64	104
22/4/2019	1,750	260	255	50	24	288	770	240	137	40	32	88
29/4/2019	1,750	244	245	19	68	340	710	310	141	60	28	210
6/5/2019	1,750	290	243	28	72	330	790	220	135	34	34	190
7/5/2019	1,740	224	254	29	44	410	790	218	133	35	32	102
9/5/2019	1,760	212	246	19	58	398	800	260	131	35	48	98
13/5/2019	1,750	240	249	40	32	290	810	220	134	29	42	102
14/5/2019	1,750	228	250	19	62	374	710	232	136	36	36	104
21/5/2019	1,750	216	253	9	72	364	840	218	139	29	41	95

sized 2 kW_p solar system was coupled with an RO plant through 5 kVA hybrid inverter to keep the capital cost at the lower side. The experiments were conducted in terms of no tracking and three-point manual PV tracking, cooling, and no-cooling of PV system and quality analysis of water. The results showed that 18% of higher PV energy was obtained throughout the day using the tracking of the PV system under local climatic conditions. Similarly, 10% higher PV energy was obtained due to the cooling of PV panels as compared to no-cooling. The cell temperature of PV panels during different months showed that the PV cooling is required during the summer season while in the winter season the cooling of panels is not required. It was also found that during continuous RO operation from 09:00 am to 05:00 pm in a day, the contribution of solar energy was higher during noontime due to high solar radiation while the share of grid energy was higher in the morning and evening time. The hybrid nature of PV–RO not only helped to reduce capital investment but significantly reduced the operational cost of the RO system.

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References

[1] UNESCO, The 2nd UN World Water Development Report: Water, A Shared Responsibility, New York, 2006, p. 134.
[2] S.A. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci., 31 (2005) 242–281.
[3] N. Ghaffour, J. Bundschuh, H. Mahmoudi, M.F.A. Goosen, Renewable energy-driven desalination technologies: a comprehensive review on challenges and potential applications of integrated systems, Desalination, 356 (2015) 94–114.
[4] M.A. Abdelkareem, M. El Haj Assad, E.T. Sayed, B. Soudan, Recent progress in the use of renewable energy sources to power water desalination plants, Desalination, 435 (2018) 97–113.
[5] E.S. Ali, A.S. Alsaman, K. Harby, A.A. Askalany, M.R. Diab, S.M.E. Yakoot, Recycling brine water of reverse osmosis desalination employing adsorption desalination: a theoretical simulation, Desalination, 408 (2017) 13–24.
[6] C. Charcosset, A review of membrane processes and renewable energies for desalination, Desalination, 245 (2009) 214–231.
[7] G.E. Ahmad, J. Schmid, Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems, Energy Convers. Manage., 43 (2002) 2641–2649.
[8] W. Gocht, A. Sommerfeld, R. Rautenbach, Th. Melin, L. Eilers, A. Neskakis, D. Herold, V. Horstmann, M. Kabariti, A. Muhaidat, Decentralized desalination of brackish water by a directly coupled reverse-osmosis-photovoltaic-system - a pilot plant study in Jordan, Renewable Energy, 14 (1998) 287–292.
[9] B.S. Richards, A.I. Schäfer, Design considerations for a solar-powered desalination system for remote communities in Australia, Desalination, 144 (2002) 193–199.
[10] E. Tzen, K. Perrakis, P. Baltas, Design of a stand-alone PV-desalination system for rural areas, Desalination, 119 (1998) 327–334.
[11] S.A. Kalogirou, Effect of fuel cost on the price of desalination water: a case for renewables, Desalination, 138 (2001) 137–144.
[12] S. Bouguecha, B. Hamrouni, M. Dhahbi, Small scale desalination pilots powered be renewable energy sources: case studies, Desalination, 183 (2005) 151–165.
[13] M.F.A. Goosen, H. Mahmoudi, N. Ghaffour, Today's and future challenges in applications of renewable energy technologies for desalination, Crit. Rev. Env. Sci. Technol., 44 (2014) 929–999.
[14] W. He, Y. Wang, M.H. Shaheed, Stand-alone seawater RO (reverse osmosis) desalination powered by PV (photovoltaic) and PRO (pressure retarded osmosis), Energy, 86 (2015) 423–435.
[15] C. Liu, K. Rainwater, L.F. Song, Energy analysis and efficiency assessment of reverse osmosis desalination process, Desalination, 276 (2011) 352–358.
[16] S.M. Shalaby, Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: a review, Renewable Sustainable Energy Rev., 73 (2017) 789–797.
[17] E. Dimitriou, P. Boutikos, E.Sh. Mohamed, S. Koziel, G. Papadakis, Theoretical performance prediction of a reverse osmosis desalination membrane element under variable operating conditions, Desalination, 419 (2017) 70–78.
[18] M. Wilf, K. Klinko, Optimization of seawater RO systems design, Desalination, 138 (2001) 299–306.
[19] M. Wilf, C. Bartels, Optimization of seawater RO systems design, Desalination, 173 (2005) 1–12.
[20] A. Ghermandi, R. Messalem, Solar-driven desalination with reverse osmosis: the state of the art, Desal. Wat. Treat., 7 (2009) 285–296.
[21] M.S. Khalil, N.A. Khan, I.A. Mirza, Renewable Energy in Pakistan: Status and Trends, University of Engineering and Technology, Taxila-Pakistan Alternate Energy Development Board, Islamabad, Pakistan, 2003.
[22] C. Fritzmann, J. Löwenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination, Desalination, 216 (2007) 1–76.
[23] M. Wilf, Fundamentals of RO-NF Technology, Proceedings of International Conference on Desalination Costing Held at Middle East Desalination Research Center, Limassol, Cyprus, 2004.
[24] R. Eke, A. Senturk, Performance comparison of a double-axis sun tracking versus fixed PV system, Sol. Energy, 86 (2012) 2665–2672.
[25] M. Dakkak, A. Babelli, Design and performance study of a PV tracking system (100W-24V DC/220V AC), Energy Procedia, 19 (2012) 91–95.
[26] B.J. Huang, F.S. Sun, Feasibility study of one axis three positions tracking solar PV with low concentration ratio reflector, Energy Convers. Manage., 48 (2007) 1273–1280.
[27] H. Bentaher, H. Kaich, N. Ayadi, M. Ben Hmouda, A. Maalej, U. Lemmer, A simple tracking system to monitor solar PV panels, Energy Convers. Manage., 78 (2014) 872–875.