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Performance of a photovoltaic powered reverse osmosis system under local climatic conditions

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Abstract

In addition to shortage of fresh water resources, Jordan is suffering from shortages in recoverable commercial energy sources such as crude oil and natural gas. The limited energy sources in Jordan makes considering renewable energy options such as solar power very attractive, especially for remote areas. This will be extremely important for small-scale applications. Due to prevailing tough conditions, such as low water quality and shortage in supplies, there is a large demand for small desalination units, not only in locations not connected to a water supply network, but also as units for additional or independent supply. In this paper, an experimental study was conducted to investigate the potential of the development of water desalination using photovoltaic powered system in Jordan. A testing rig was built, where a reverse osmosis (RO) desalination system driven by photovoltaic power is used. The RO unit consists of a five-micron sediment filter that is made of polypropylene, two active carbon filters with 1–2 micrometer hole diameter, and one polyamide TFC membrane. The system is mechanically powered, directly coupling the photovoltaic power system to a DC motor, which is coupled to a pump that is capable of providing sufficient torque to run the RO system. Two PV arrays are connected in series and tilted a 32° to the south. To study the effect of tracking on the performance of the system, a one-axis east–west tracking flat plate photovoltaic is constructed. Results for both, the fixed flat plate and the one-axis tracking system were compared. Output electrical current, voltage and power of pump's motor were measured. Pure water flow rate, TDS and PH of produced water were measured for both systems. Analysis of results show that a gain of 25 and 15% of electrical power and pure water flow, respectively, could be achieved using the east–west one-axis tracking system compared with fixed flat plate.

Keywords: Photovoltaic power; Reverse osmosis; Tracking system; Jordan; Water quality

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1. Introduction

Jordan is characterized by an arid to semi-arid climate, where rainy seasons are short and annual rainfall intensities range from 50 to 600 mm. On the other hand, Jordan's population is increasing at a yearly rate of 3.6%. The yearly consumption of fresh water per capita is 200 m^3 in comparison to the world's yearly average, 7500 m^3. Jordan's water resources comprise surface water (41%), renewable and non-renewable ground water (54%) and treated wastewater (5%), which is used by agriculture (69%), industry (10%) and municipalities (21%). With such high population growth rate and the fast socio-economic development, a steep increase in water demand and wastewater production is occurring and the gap between water supply and demand is getting wider. Simultaneously, the constraints for water resource development are increasing due to high investment costs and water quality degradation caused by over exploitation of ground water resources (increasing salinity to 0.2–3 g/L). The severity of this problem have been realized since the beginning of the 80s and according to recent projections of water supply and demand, Jordan is likely to face a potable water crisis by 2010, by depleting all of its fresh water sources. Thus, it is likely to suffer tough water-rationing early this decade if integrated measures are not immediately taken to ensure water availability, suitability and sustainability. Anyhow, the adoption of non-conventional options for water supply enhancement is inevitable in the near future for Jordan sustainable development. There are a few options to supplement the conventional water supply, e.g. irrigation by saline water, desalination of brackish or sea water, reuse of treated municipal wastewater, rain water harvesting, cloud seeding and water importation [1–4]. Desalination has been widely used in Middle Eastern oil-producing countries.

Desalination processes require considerable amounts of energy to achieve separation of dissolved salts in seawater or brackish water. It has been estimated [5] that the production of 1000 m^3/d of fresh water requires 10,000 tons of oil per year. This is highly significant as it involves a recurrent energy expense, which few of the water-short areas of the world can afford. Even if oil were much more widely available, given the current understanding of the greenhouse effect and the importance of carbon dioxide levels in the atmosphere, environmental pollution caused by burning fossil fuel for desalination is a major concern. The thermal energy required for desalination using thermal-driven distillation processes can be achieved by collection of solar energy using flat collectors, evacuated tube collectors or solar ponds. Such devices can achieve temperatures of 80–130°C, which are quite suitable for such desalination processes. Solar energy can also be converted to electrical power using either photovoltaic panels or high-temperature concentrating collectors associated with a heat engine operating on thermodynamic cycle. Such electrical power can then be used to operate power–driven desalination processes such as reverse osmosis or vapor compression. Conventional desalination is energy intensive. Thus, one of the major concerns to developing water production by desalination is the cost of energy. Apart from the cost implications, there are environmental concerns with regard to the burning of fossil fuels. The coupling of renewable energy sources with desalination processes is seen by some as having the potential to offer a sustainable route for increasing the supplies of potable water.

Although water and energy resources are scarce in Jordan, desalination of water from Red Sea/Aqaba Gulf (TDS = 40 g/L) or desalination of brackish water from some basins (TDS = 1–10 g/L) emerging in the form of springs throughout the kingdom might be economically feasible by efficient use of non-conventional energy resources. In fact, brackish waters in Jordan are sought as potential and viable resources to cope with water scarcity and overcome water deficit, according to several recent studies:

- Sea or brackish water desalination are the most favorable non-conventional water resources, based on criteria of reliability, availability, economic and technical feasibility and environmental sustainability [6].
- Hydropower and solar technologies are the most effective non-conventional energy resources for water desalination, bearing in mind water productivity and environmental sustainability criteria [1].
- Desalination of sea or brackish water by RO appears to be a sound alternative to arid lands bordering seas or salt lakes, in terms of technical and economic feasibility and environmental sustainability. Seawater desalination would be obviously more expensive [7].

In this paper, an experimental study was conducted to investigate the potential of the development of water desalination using photovoltaic powered system in Jordan. A testing rig was built, where a reverse osmosis (RO) desalination system driven by photovoltaic power is used. The system is mechanically powered, directly coupling the photovoltaic power system to a DC motor, which is coupled to a pump that is capable of providing sufficient torque to run the RO system. Two PV arrays are connected in series and tilted a 32° to the south. To study the effect of tracking on the performance of the system, a one-axis east–west tracking flat plate photovoltaic is constructed. Results for both, the fixed flat plate and the one-axis tracking system were compared.

2. Solar energy in Jordan

In Jordan, the average insolation intensity on a horizontal surface is approximately 5–7 kWh/m^2-d, which is one of the highest in the world [8]. The solar water-heating industry in the country is well developed. By 1999, about 25% of homes (i.e. 2.3×10^5 homes) had been fitted with solar water-heaters [4], thereby avoiding the need for approximately 2% of the total oil imports, with an associated savings of about 12 million $US annually, depending on crude oil prices. In addition, Jordan is considered to be the lead country in the world in utilizing solar energy for industrial purposes. Solar energy is employed to evaporate $\sim 90\times 10^6$ m^3 annually of the Dead Sea water in the process of potash and other salts production, thereby avoiding approximately 4×10^6 toe of fuel oil having to be imported annually.

Photovoltaic systems are employed, in some remote regions, for water-pumping systems, powering radiotelephone stations, as well as supplying electrical energy for clinics, schools, and a few small villages. Other applications of solar energy, such as passive heating and cooling of buildings and food drying are under consideration.

3. Potential and quality of brackish groundwater

In Jordan, two main sources are available to be desalted: the Aqaba Gulf and the brackish deep groundwater in some basins. Preliminary studies showed that by the year 2010 more than 2×10^7 cm, of brackish water, could be developed in the central part of

Jordan. This figure may reach 7×10^7 cm by the year 2040. According to the water quality analysis conducted by the Japanese International Cooperation Agency (JICA) on brackish water in the Jordan, the total dissolved solids results were in the range of 5000–10,000 ppm [9].

Brackish-water resources can provide over 5×10^7 m^3 annually for the cultivation of salt-tolerant crops or when desalinated, for domestic and/or industrial purposes.

Thermal-desalination processes, though relatively expensive, could be employed successfully to supply potable water. However, this is unlikely to occur, on a large scale, until locally available oil shale is burnt in fluidizedbed combustors to produce the required energy supply. However, desalination using waste heat (i.e. hot flue-gases at temperatures exceeding 500°C) from gas-turbine power stations will be implemented in Jordan sooner. These power stations utilize mainly simple open-cycle gas-turbine technology, because of fresh-water shortages, which tend to negate the use of combined-cycle technology.

Whether or not direct solar distillation is worthwhile for a particular location in Jordan depends upon the local prevailing conditions, such as high insolation intensity, the ready availability of adequate supplies of low-quality water, as well as having sufficient funds to meet the capital and operating costs. However, the rate of fresh-water required and its end use are crucial in determining the suitability of this process. It has been estimated that a solar-desalination system in remote regions can satisfy a potable-water demand of around 95 m^3/d economically. However, for yields exceeding 190 m^3/d, non-solar methods appear to be more economic. This is because of the high capital and labor costs for water desalination by solar systems at high rates of production.

The brackish water quality varies from one location to another. Based on the water quality analyses that had been carried out by JICA study team [9], the salinity of water is around 5000–10,000 mg/L as TDS with water temperature of 32–36°C. NaCl is the main component of salt in water (3000–6000 mg/L). Besides, the cations of Ca, Mg and the anions of SO_4 and HCO_3 that are considered to be scaling substances exist in relatively high concentrations, and the calculated total hardness is in the range of 1500–3000 mg/L as $CaCO_3$. The Fe concentration is 5–15 mg/L. As for SiO_2, which is a fouling substance for membranes, its concentration is in the range of 10–20 mg/L.

4. Reverse osmosis desalination system

Desalination is a separation process used to reduce the dissolved salt content of saline water to a usable level. All desalination processes involve three liquid streams: the saline feed water, low-salinity product water, and very saline concentrate (brine or reject water).

RO is a pressure driven process that separated two solutions with differing concentrations across a semi-permeable membrane. The rate at which fresh water crosses the membrane is proportional to the pressure differential across the membrane that exceeds the natural osmotic pressure differential. The membrane itself represents a major pressure differential to the flow of fresh water. No heating or phase change take place. The major energy requirement is for the initial pressurization of the feed water. For brackish water desalination the operating pressures range from 250 to 400 psi, and for seawater desalination from 800 to 1000 psi. As fresh water permeates across the membrane, the feed water becomes more and more concentrated. There is a limit to the amount of fresh water that can be recovered from the feed without causing fouling of the membranes. Seawater RO plants have recoveries from 25 to 45%, while brackish water RO plants have a recovery rates as high as 90%. The RO system major components include membrane modules, high-pressure pumps, power plant, and energy recovery devices as needed. Brackish or seawater at a high pressure, greater than the osmotic pressure is fed through the membrane. Two major factors controlling the energy requirement of an RO system are membrane properties and salinity of the feed water [4]. Higher water salinity requires more energy to overcome the osmotic pressure, where the RO system needs only mechanical power to raise the pressure of feed water. Other advantages of RO systems include low investment costs at low capacities, ease of operation, flexibility in capacity expansion, operation at ambient temperature and short construction periods.

5. Experimental work

Generally, a PV system consists of PV arrays, batteries, a controller, an inverter and several types of load. Its performance depends on several factors especially the meteorological conditions such as solar radiation. To use the PV system efficiently and economically, the PV systems are necessary to be designed under the local condition of load, irradiation, temperature and their components' characteristics.

A RO desalination system driven by solar energy is proposed. The system is mechanically powered, directly coupling the photovoltaic power system to a DC motor coupled to a pump, which is capable of providing sufficient torque to run the RO desalination system.

A schematic diagram of the photovoltaic powered reverse osmosis system used in this study is presented in Figs. 1 and 2. Fig. 1 shows the fixed axis photovoltaic system, two PV arrays are connected in series and tilted a 32° south. The rated voltage, current and power are 17.9 V, 2.1 A and 35 W, respectively. Two PV arrays with the same specifications were used in an east–west tracking system as shown in Fig. 2. The driving motor was controlled by a Siemens LOGO 24RC PLC microcontroller, that uses functional programming language, The RO unit consists of a five-micron sediment filter that is made of polypropylene fiber to treat the suspended solids, two active carbon filters with 1–2 micrometer hole diameter, both are made of strengthen active carbon, the front

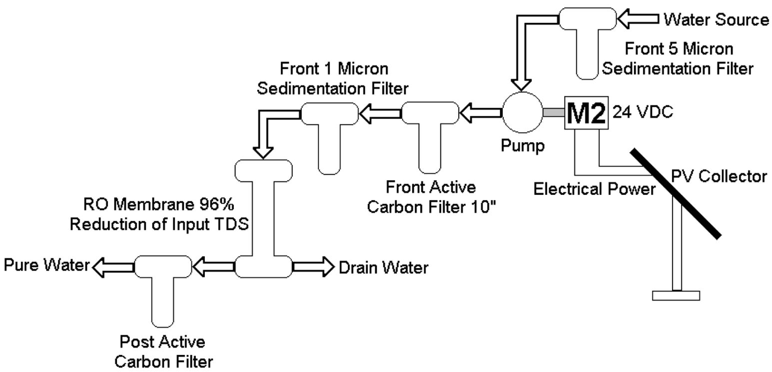

Fig. 1. Schematic diagram for fixed surface PV collector integrated with RO unit.

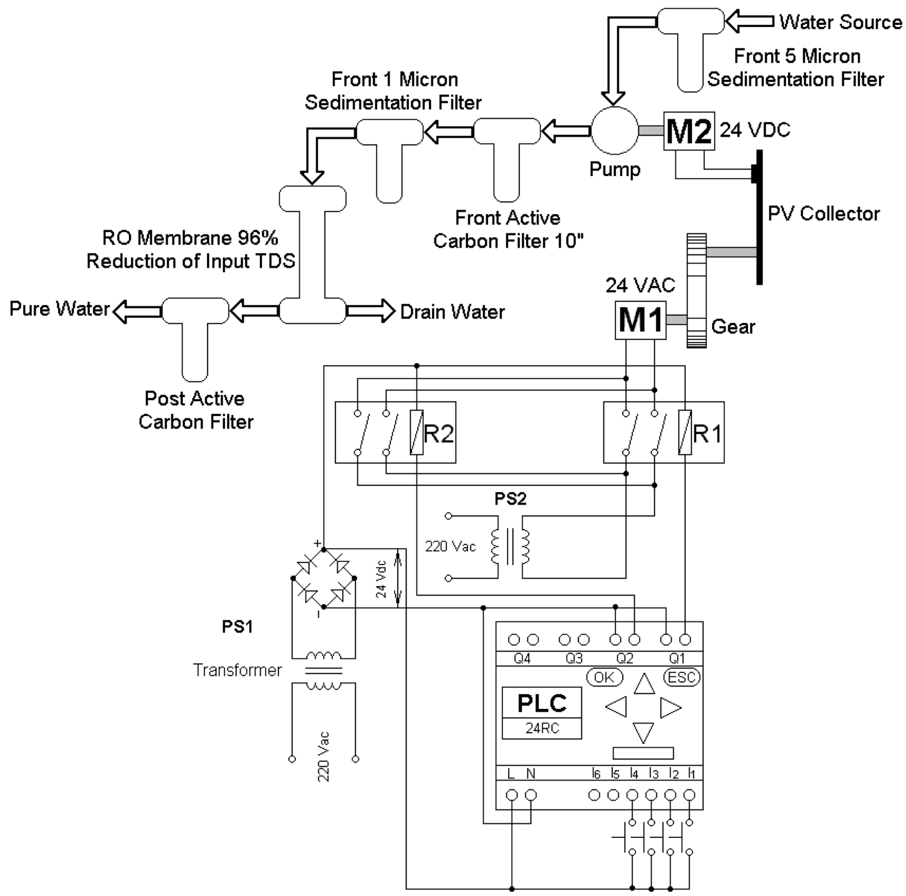

Fig. 2. Schematic diagram for east–west tracking PV collector integrated with RO unit.

filter is used to treat organic substances and the post active carbon filter is to treat odor, taste, Ti, Cu, Zn, Fe, Cd, As, Hg, Ph and other compounds. The one micron sediment filter is made of especially fine fiber to handle rust, sand, lime, soil and colloid substances. The RO unit is equipped with one polyamide TFC membrane. It is 45 mm in inside diameter and 240 mm long. The permeate and concentrate flow rates were measured with a stopwatch and a graduate cylinder. The concentrate flow rate and the transmembrane pressure were controlled manually by the by pass valve and the needle valve at the outlet module.

6. Results and discussion

In order to study the performance of the proposed photovoltaic powered RO system, experiments were conducted in the Renewable Energy Center of the Applied Science University at Amman, Jordan during the month of April. The results reported were for sunny to mostly sunny days. Tap water was used as the input flow for the system with a TDS of about 400 mg/L and an average of 7.9 pH.

For an experiment conducted on the 5th day of April for a fixed surface and one-axis east–west tracking system, Figs. 3 and 4 present the variation of the output electrical

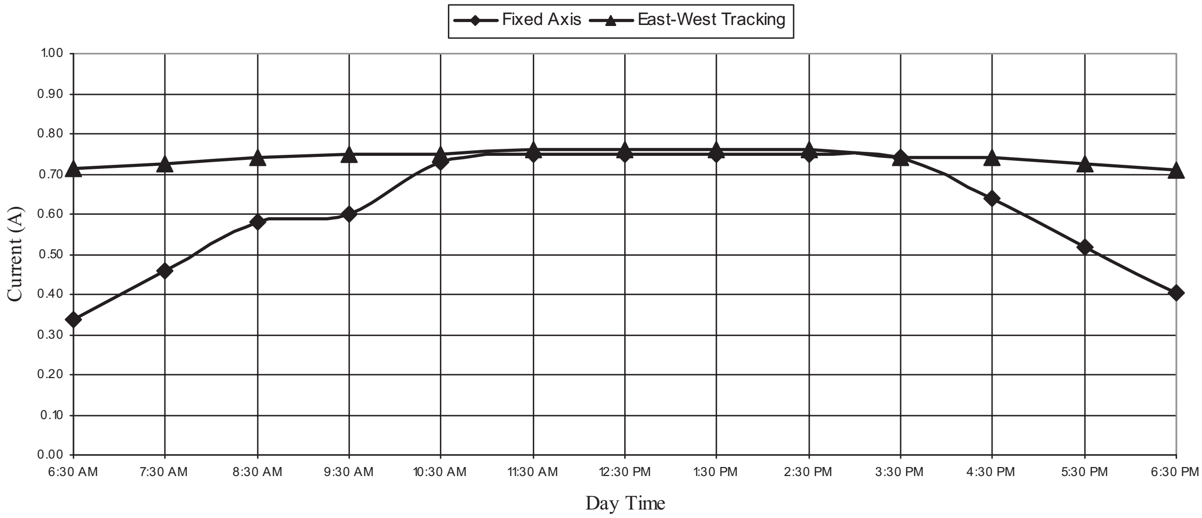

Fig. 3. Electrical current for fixed surface and tracking PV systems as a function of the hour of the day.

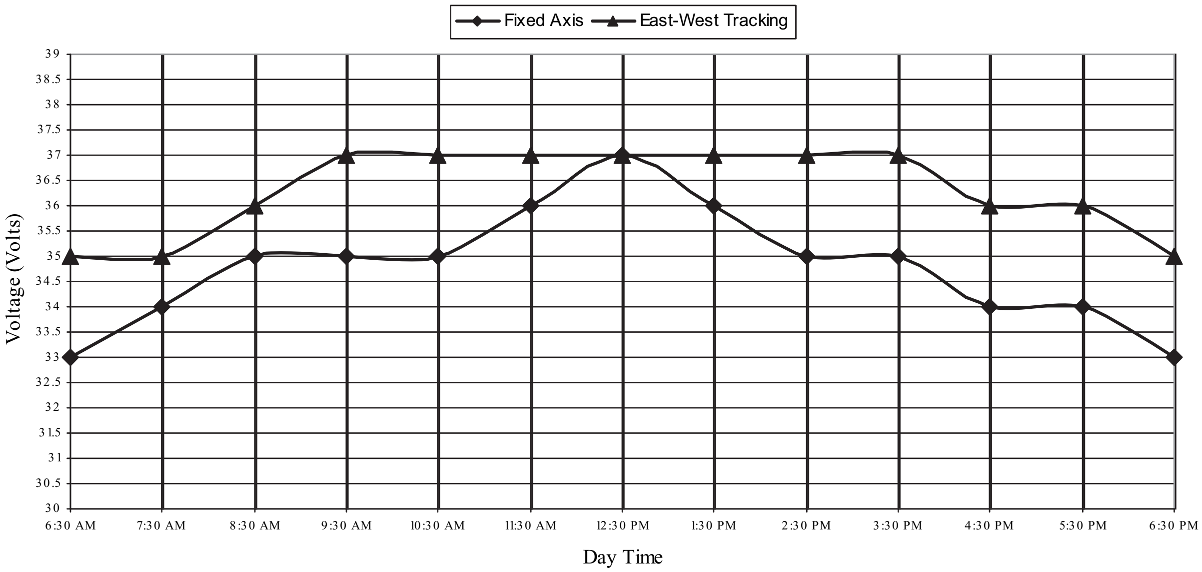

Fig. 4. Electrical voltage for fixed surface and tracking PV systems as a function of the hour of the day.

current and voltage, respectively. Measurements were recorded at 60 min time interval, starting 6:30 am and ending at 6:30 pm. The maximum current for both systems always occurred between the hours of 10:30 am to 3:30 pm. It was about 0.78 A. The maximum voltage of 37 V for the fixed surface was achieved at 12:30 pm, while the same value was achieved by the tracking system between the hours of 9:30 am to 3:30 pm. The electrical power of the motor operating the pump for both systems is shown in Fig. 5. It ranged between 25 and 28 W for the tracking system between the hours 6:30 am and 6:30 pm, the

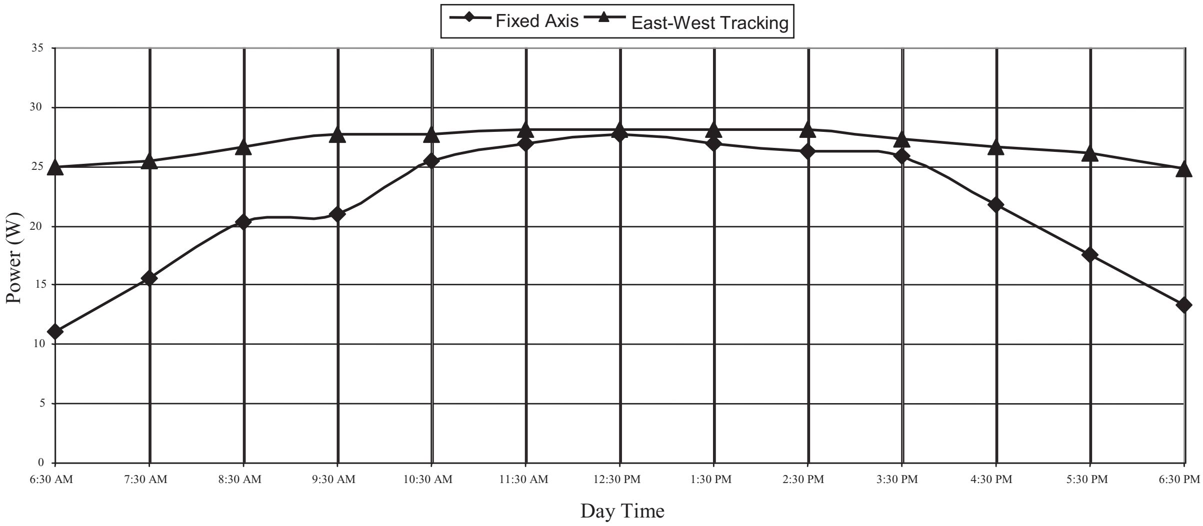

Fig. 5. Electrical power for fixed surface and tracking PV systems as a function of the hour of the day.

same range was recorded for the fixed surface between the hours 10:30 am and 3:30 pm.

The flow rates of desalinated water for both systems as functions of time and electrical power are shown in Figs. 6 and 7, respectively. A maximum of 0.180 L/min flow rate was recorded for the tracking system at 12:30 pm, while the maximum for the fixed surface was 0.16 L/min at 1:30 pm. Both flow rates were recorded at a power of 28.1 W.

The average values of the TDS and pH of the desalinated water were measured to be

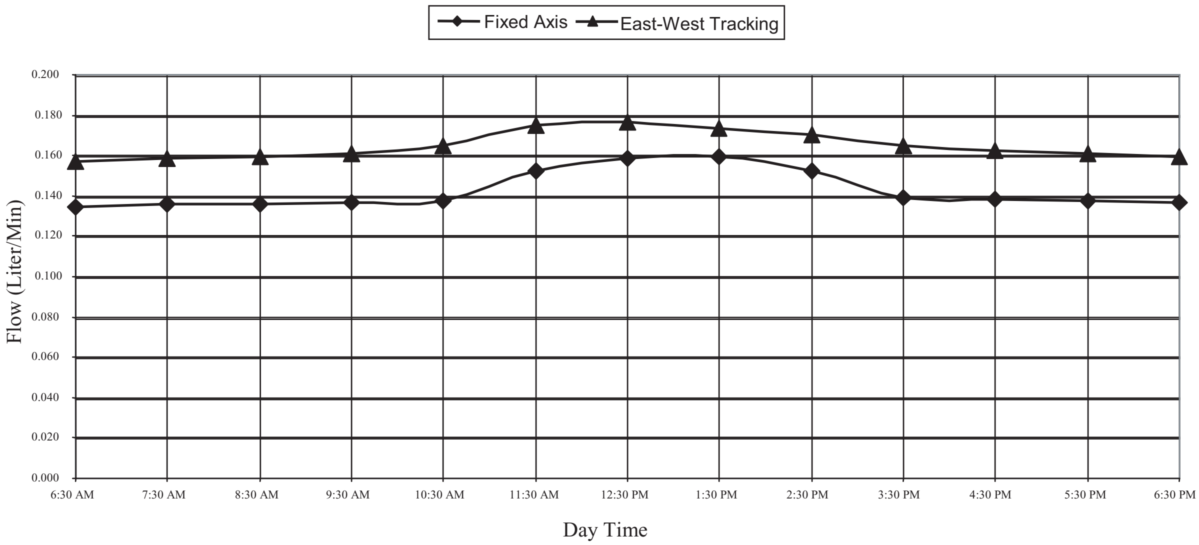

Fig. 6. Desalinated water flow rate for fixed surface and tracking PV systems as a function of the hour of the day.

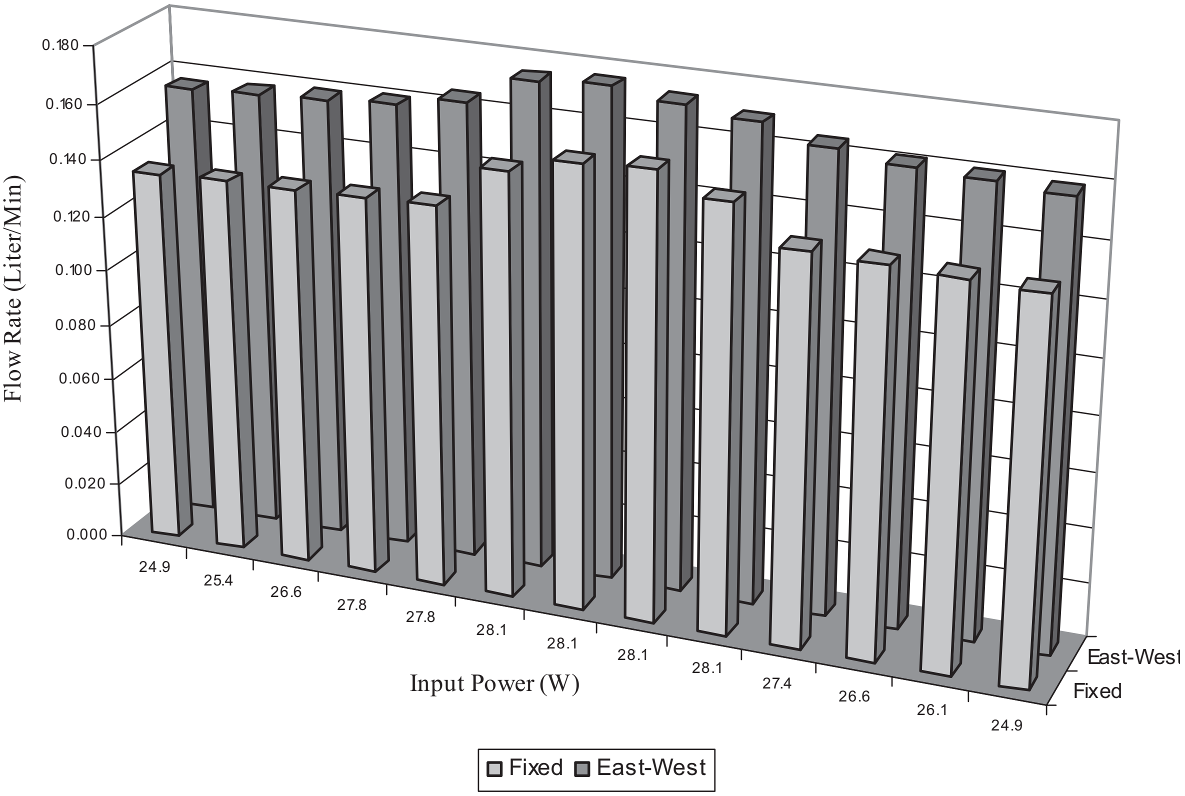

Fig. 7. Desalinated water flow rate for fixed surface and tracking PV systems as a function of electrical power.

20 mg/L and 7.2, compared to 400 mg/L and 7.9, respectively.

7. Conclusions

The results show that the photovoltaic powered RO system has a favorable application. For the RO system considered in this paper, it can be concluded that a gain of 25 and 15% of electrical power and desalinated water flow, respectively, could be achieved using the east–west one-axis tracking system compared with fixed flat plate. More experimental work needs to be carried out to study the continuous performance of the system, and more investigations should be directed to the membrane fouling and recovery ratio of the system.

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