Desalination and Water Treatment
www.deswater.com

7 (2009) 53–59

Laboratory setup for water purification using household PV-driven reverse osmosis unit

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Received 25 August 2008; accepted in revised form 22 February 2009

ABSTRACT

Water treatment using renewable energies as a power source is still not common due to the high initial investment cost. The possibility of using photovoltaics (PV) as a power source to run a household RO unit has been investigated. Experiments on the laboratory household unit were performed using water with two different total dissolved solid (TDS) concentrations (350 mg/L and 720 mg/L). During the period from February 28, 2007 to November 30, 2007 the unit was entirely powered by photovoltaic cells and operated with and without storage batteries. Without batteries the rate of production of fresh water varied throughout the day according to the available solar power, but was steady when operated with batteries. The specific energy consumption ranged from 1.1 kWh/m^3 to 4.3 kWh/m^3 for the battery system and ranged from 1.1 kWh/m^3 to 1.5 kWh/m^3 for the battery-less system. Two membranes (CSM and FILMTEC) were utilized. The CSM membrane was used from February 28, 2007 to June 18, 2007 (period of storage batteries), while the FILMTEC membrane was used during the battery-less period from October 1, 2007 to November 30, 2007. The FILMTEC membrane performed better than the CSM membrane, producing, on average, 8 L/h of drinking water (about 16 mg/L. TDS) at specific energy consumption of 1.3 kWh/m^3. Several effects on the performance of the RO unit were investigated, but the temperature effect was the most significant.

Keywords: Reverse osmosis; Water treatment; Photovoltaics; Energy consumption

1. Introduction

Desalination of sea or brackish water has become one of the most important ‘non-conventional’ growing sources of drinking water in many parts of the world, and plays already an important role in solving fresh water scarcity in areas where other water supply sources are not available [1]. Desalination is the process of bringing down the salinity of sea or brackish water from a high level of total dissolved solids of 35,000 ppm to an acceptable level of 500 ppm [2]. This is achieved by separating saline water into two streams: one with a low concentration of dissolved salts (the fresh water stream) and the other containing the remaining dissolved salts (the concentrate or brine stream). This process requires energy to operate and can use a number of different technologies for separation. The process of desalination can be classified into two categories based on the consumption of energy, namely, thermal and non-thermal processes. Thermal processes include multi stage flash (MSF), multi effect (ME) and vapor compression (VC). These processes produce very high quality water but large amounts of thermal energy in the form of steam and electrical energy are required

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Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

in seawater distillation plants. For this reason thermal distillation plants are usually coupled to power plants.

Non-thermal processes or membrane technology like reverse osmosis (RO) and electrodialyses (ED) have gained a significant part of the desalination market at the expense of distillation [3]. Salt water can be desalted and supplied in large quantities and with a very high quality, but this requires a great amount of energy, the overwhelming majority of which is obtained from fossil fuels. Therefore, the future of desalination is linked to the problem of conventional energy source availability, possible depletion and cost, as well as the environmental impact. Renewable energy resources are basically the alternative answer to petroleum depletion and its contaminant power. In the last decades a remarkable progress has been achieved regarding renewable energy, its exploitation and dissemination, although there is still a lot to do before it becomes profitable [1].

Desalination matching with solar energy offers a promising future prospect for covering the fundamental needs of fresh water in remote arid areas, where the connection to the public electrical grid is not economical or is not feasible. Coupling desalination systems with solar energy is of great importance to both environment and production costs.

In view of the above, this work focuses on the study of two well-established technologies and their integration: water desalination by reverse osmosis (RO) and electricity generation using solar energy (photovoltaic technology).

A small PV–RO system was installed and tested in the campus of the Jordan University of Science and Technology. This system was operated with and without storage batteries. The paper aims to present the results obtained from that system.

2. Experimental setup

A process flow diagram of the household PV–RO system is shown in Fig. 1. The system has five major components: an RO unit with proper pre-filters, PV modules, battery storage, a solar regulator and a feed tank. The technical specifications for each component are shown in Table 1. Through the period from February 28 2007 to November 30, 2007 the RO unit was entirely powered by PV cells and operated with and without storage batteries.

Feed water was treated from its preliminary contamination in three stages: (1) 5 micron filter, removes sediment, clay, silt and particulate matter to 5 micron range (2) carbon filter removes chlorine, harmful chemicals, synthetic detergents, as well as other organic contaminants, and (3) compacted carbon block, where a combination of mechanical filtration and physical/chemical adsorption takes place to reduce or eliminate a wide range of contaminants.

RO units available in the market are normally of the AC type, single phase or three phases. There are some DC units but their prices are higher, and they need more maintenance. The inverter is needed to change the DC output power of the PV panel to AC power. According to the system design, the inverter is required to handle the peak power of the PV array, and its input and output voltages must be suitable for the operation of the battery and RO unit. The selected inverter has the specifications of 12 VDC/230 VAC single phase 150 W.

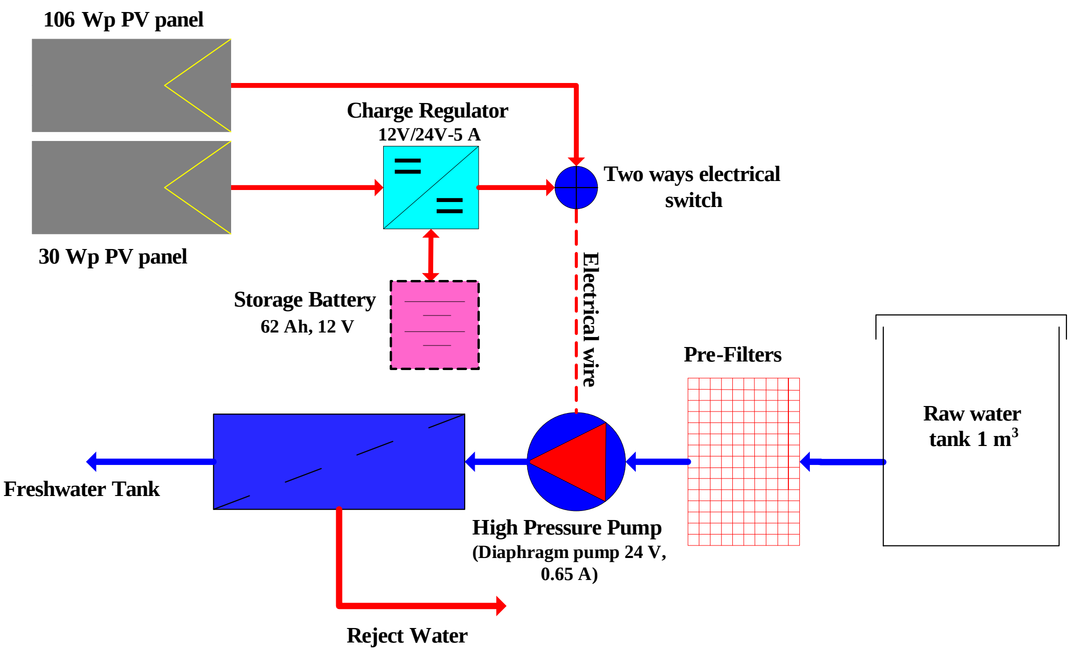

Fig. 1. Process flow diagram of the household system.

Table 1
Household PV–RO system technical description

Item	Specifications	Item	Specifications
106 Wp PV panel	ISOFOTON technology (I-106/12), Germany	FILMTEC membrane TW30-1812-75	FILMTEC household RO membrane, USA
	Short circuit current I_{sc} = 6.52 A		Membrane type: thin-film composite
	Open circuit voltage V_{oc} = 21.6 V		Membrane material: PA (polyamide)
	Maximum power current I_m = 6.10 A		Permeate flow rate = 12 L/h (75 gal/d)
	Maximum power voltage V_m = 17.4 V		Max. operating temperature: 45°C (113°F)
	Area = 0.85 m^2 (mono crystalline type)		Max. operating pressure: 300 psi (21 bar)
30 Wp PV panel	SOLARA technology (SP30.36A), Germany		Max. feed flow rate: 2 gpm (7.6 lpm)
	Short circuit current I_{sc} = 1.837A		pH rang continuous operation: 2–11
	Open circuit voltage V_{oc} = 24 V		pH rang short term cleaning: 1–13
	Maximum power current I_m = 1.67 A		Maximum feed SDI: 5
	Maximum power voltage V_m = 18 V		Free chlorine tolerance: $<$ 0.1 ppm
	Area = 0.60 m^2 (mono crystalline type)	Batteries	FISION technology, China
Solar regulator	JUTA technology, China		62 Ah, 12 V
	12V/24V-5 A volt automatic detection	HPP	Diaphragm pump (24 V, 0.65 A)
CSM membrane RE-1812-70	CSM household RO membrane, China		Max. operating pressure 125 psi
	Membrane type: thin-film composite		Open flow = 1.75 L/min
	Membrane material: PA (polyamide)	Feed pump	SHURFLO technology, Germany
	Membrane surface charge: negative		12 VDC, 10 A
	Element configuration: spiral-wound, tape wrapping		Operating flow 3.6 gpm (13.6 L/min)
	RO unit recovery ratio = 50%		Operating pressure 45 psi
	Nominal salt rejection = 96%	Feed tank	1 m^3 tank
	Permeate flow rate = 265 L/d (70 gal/d)	Built-out controls (online)	Feed and permeate conductivity meter (WTW, Germany)
	Max. ooperating pressure 125 psi (0.86 MPa)		Feed flow meter (Krohne, Germany), permeate flow meter (BIO-Technology, USA)
	Max. feed flow rate 2 gpm (0.45 m^3/h)		Ambient and water temperature sensors (B&B, Germany)
	Max. operating temperature 45°C		Pyranometer sensor (Kipp & Zonen, Germany)
	Operating pH range 3.0~10.0		Data acquisition system (Agilent Technologies, Germany)
	Max. turbidity 1.0 NTU		
	Max. SDI (15 min) 5.0		
	Max. free chlorine concentration 0.1 mg/L		

Ambient temperature, irradiation, as well as flow and conductivity for both feed and permeate streams were measured online and stored by the available data acquisition system (recorded every 10 s for later analysis).

3. Results

3.1. Meteorological data

Average values of solar irradiation (W/m^2), insolation (kWh/m^2/d), average peak sunshine hour (h) and ambient temperature (°C) were recorded for different months during the year 2007 and are presented in Fig. 2 which shows the variation of ambient temperature, solar irradiation peak sunshine hours and insolation during the year 2007. As shown, the month of August was the hottest (34.7°C) with the highest solar insolation (7.4 kWh/m^2/d).

3.2. Battery-less PV–RO system (direct operation from the PV)

Fig. 3 shows an illustrative block diagram for the PV–RO system with no battery storage. The FILMTEC membrane was used during the period of battery-less PV–RO operation.

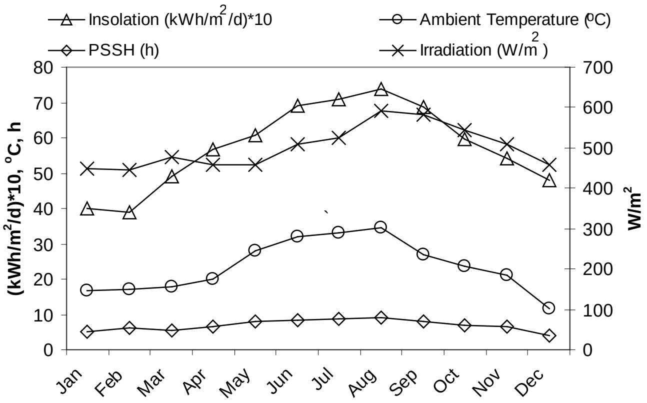

Fig. 2. Monthly average of sun insolation, irradiation and ambient temperature during the year 2007 (JUST, 2007).

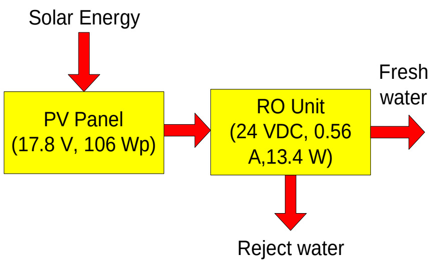

Fig. 3. Block diagram of the PV–RO system with no battery storage.

3.2.1. *Effect of solar irradiation*

The performance for a sunny day in October 2007 is shown in Fig. 4. The conductivity of feed water was 1450 μS/cm (720 mg/L). The system started operation at 7:00 AM when the solar irradiation was in the range of 200 W/m². At this value of irradiance, the feed flow reached the maximum (19 L/h) immediately, because the power generated by the PV panel was higher than the power needed by the pump. The PV panel provides electrical current directly to the high pressure pump (HPP) whose speed increases as the power from the PV panel increases. The 19 L/h is the highest flow rate that can be produced by the HPP. No more permeate flow was obtained from the unit after 4:17 PM.

The permeate flow followed the behavior of the feed flow and reached 7 L/h with 37% recovery. The total amount of permeate produced was 65 L (with 9.4 h of operation).

In the first few minutes of operation, the permeate conductivity was high (350 μS/cm) and thereafter declined to its normal level of 55 μS/cm (18 mg/L). This happened because no flushing was employed to clean the membrane after each shutdown. The average salt rejection was 97.4%.

Fig. 5 shows the global irradiation, feed flow rate, permeate flow rate and both conductivities for feed and permeate streams for a cloudy day in November 2007. The high pressure pump started at 7:30 AM when the solar irradiation reached 140 W/m², and stopped at 8:00 AM, because not enough power was available. It restarted again at 9:00 AM when the solar irradiation reached 550 W/m².

The feed flow and permeate flow, as shown, vary in direct response to the available sunlight. There were many passing clouds during that day, and, in the absence of any batteries, the arrival of each cloud caused an immediate reduction or halt of permeate flow.

The total amount of permeate collected over that day was 51 L. The permeate conductivity was about 39 μS/cm (12 mg/L), with 98.4% of salt rejection.

The intermittent operation of the system causes also slight rise in product water concentration, particularly following a break in production: a passing cloud may stop the flow of permeate water, but the salt passage through the membrane continues. Fortunately, the cloudy periods tend to coincide with low water temperature, which lower the rate of salt passage.

Fig. 6 illustrates daily production of permeate as a function of insolation. The daily production reached 83 L as maximum when the insolation was about 6.2 kWh/m². The daily production was not only dependent on the solar insolation but also on the feed temperature which varied in accordance with the ambient temperature.

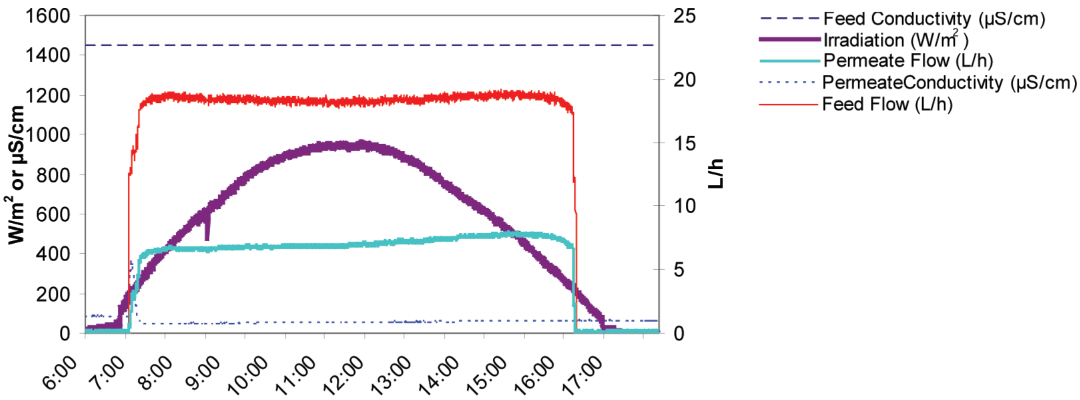

Fig. 4. Hourly variations of permeate flow and conductivity with solar irradiation for a sunny day (October 26, 2007).

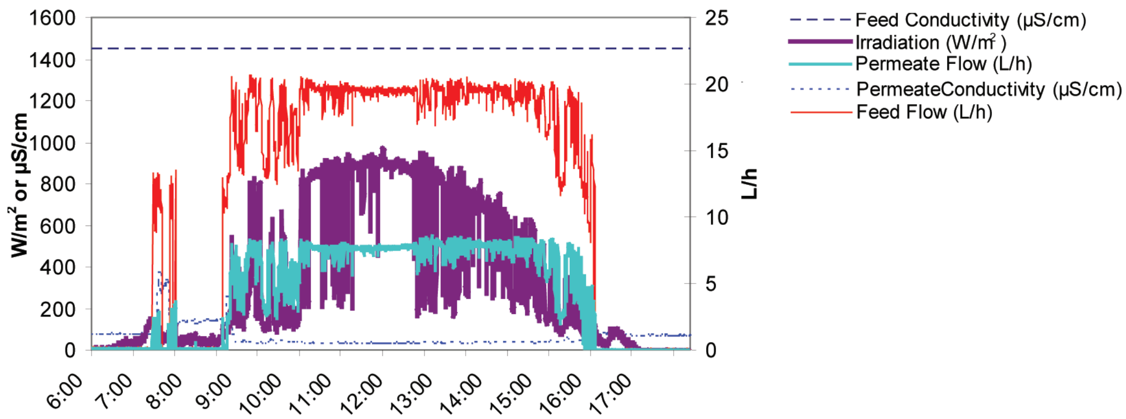

Fig. 5. Hourly variations of permeate flow and conductivity with solar irradiation for a cloudy day (November 7, 2007).

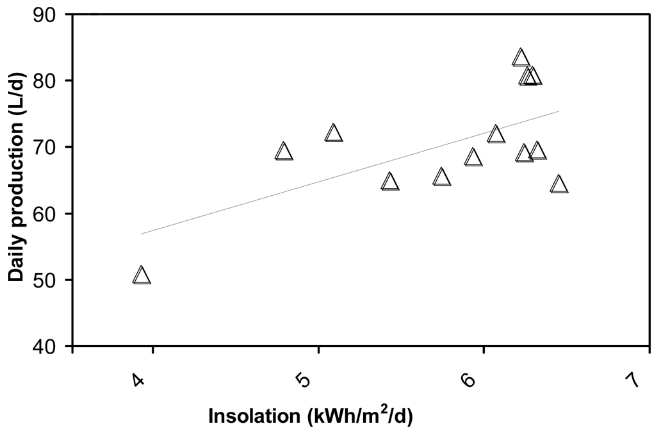

Fig. 6. Daily production as a function of insolation.

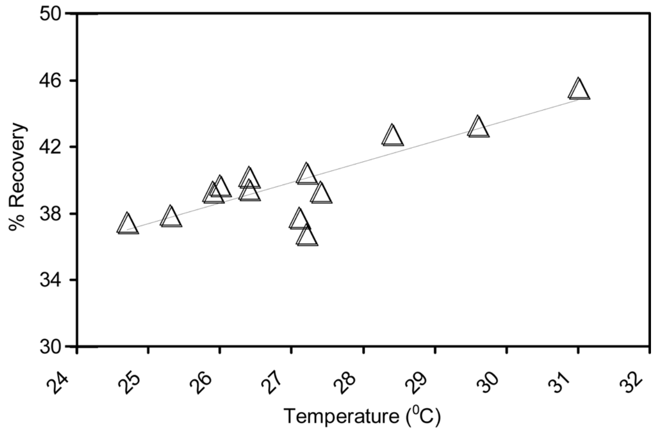

Fig. 7. Influence of the water temperature on permeate recovery.

The recovery was in the range of 37.5–45.6% while the specific energy consumption (SEC) was in the range of 1.1–1.5 kWh/m^3.

3.2.2. *Effect of feed water temperature*

Membrane productivity is very sensitive to changes in feed water temperature. As water temperature increases, water flux increases almost linearly primarily due to the higher diffusion rate of water through the membrane. Increased feed water temperature also results in lower salt rejection or higher salt passage. This is due to a higher diffusion rate for salt (salt flux) through the membrane. The opposite happens when the feed water temperature decreases.

The percentage recovery increased from 37.5% to 45.6% and salt rejection decreased from 98.4% to 96.9% when the feed temperature increased from 24.7°C to 31°C as elucidated in Fig. 7 and Fig. 8, respectively. Similar behavior was also noticed by Thomson et al. [4].

3.2.3. *Effect of feed pressure*

In order to study the effect of feed pressure on the unit performance, a feed pump powered externally (12 V, 6A) was placed before the high pressure pump of the RO unit. The feed pressure increased from 63 psi to 75 psi.

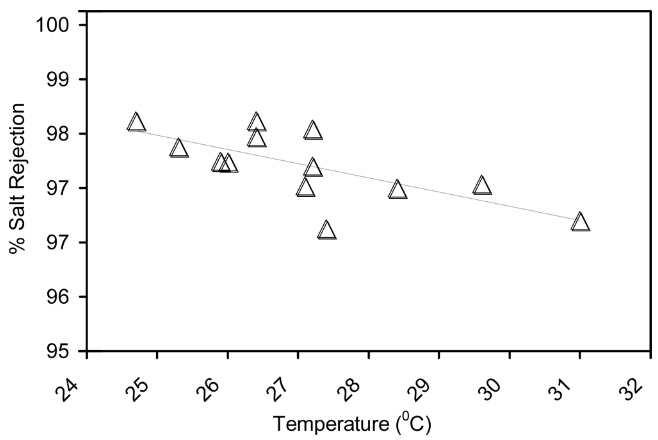

Fig. 8. Influence of the water temperature on salt rejection.

The permeate production increased by 35.9% when the feed pump was used. The feed flow reached 23 L/h and permeate flow was around 10 L/h (Fig. 9). The total

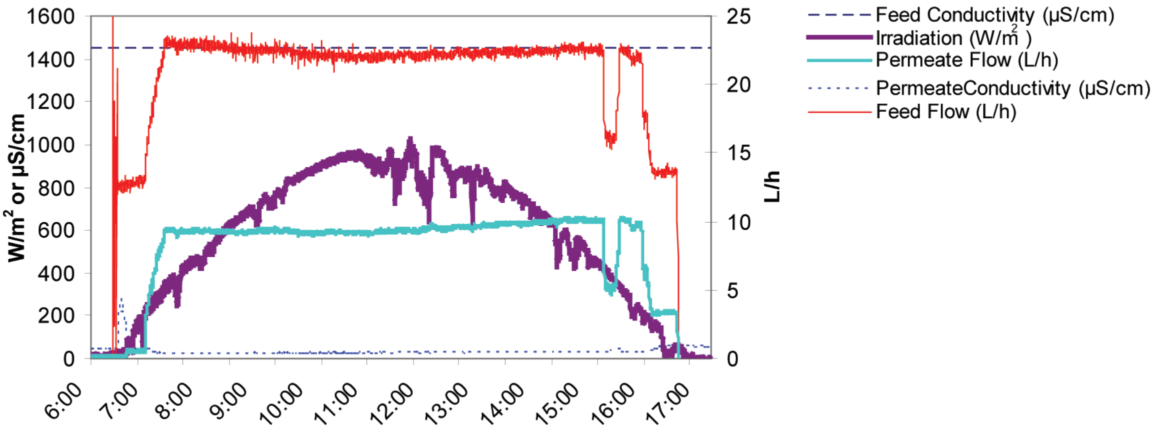

Fig. 9. Daily variations of permeate flow and conductivity with solar irradiation (November 15, 2007).

amount of permeate collected in that day was 96 L. The permeate conductivity and salt rejection were 36 µS/cm (11 mg/L) and 98.7%, respectively. Using the feed pump in the PV–RO unit actuates the system to consume more energy for desalination. Specific energy consumption increased from 1.4 to 11.3 kWh/m^3.

3.3. Battery PV–RO system (indirect operation)

Rechargeable batteries are widely used in PV systems, mostly for storing the energy during the day and making it available through the night, but also sometimes for smoothing out variations due to passing clouds. Fig. 10 shows an illustrative block diagram for the PV–RO system using battery storage. A CSM (customer satisfaction membranes) membrane was used in these tests. Two modes were followed through operating the battery PV–RO system. In mode 1, the battery was used to compensate for daily variations in solar energy while in mode 2 two batteries were used to smooth the unit production and to store the excess energy.

3.3.1. Performance

The performance of the PV–RO system with battery storage (20 Ah) is shown in Fig. 11 for a day in March 2007. The conductivity of feed water was 720 µS/cm. The feed flow was steady through the period of operation; this was due to steady current from the storage battery. The battery storage was able to operate the system for about 4 h. The total permeate water recorded over that day was 23.5 L and the permeate conductivity was about 27 µS/cm (7 mg/L). The rejection coefficient of salts was about 98%.

3.3.2. Effect of solar irradiation

Fig. 12 presents the relationship between the number of unit operating hours and the corresponding average irradiation. Increasing the value of average irradiation increases the operation hours of the unit. The surplus electrical energy was stored in the battery giving more hours of operation. The amount of permeate, increases with increasing the daily average irradiation.

3.4. Economical overview

To study the economics of obtaining pure water from raw water with salinity up to 1450 µs/cm (720 mg/L), it is necessary to estimate the initial cost and the operating cost of the system according to market prices. Table 2 summarizes the costs of the PV–RO household units. The water costs were calculated based on the following:

- Unit life: 10 years
- Interest rate: 5%

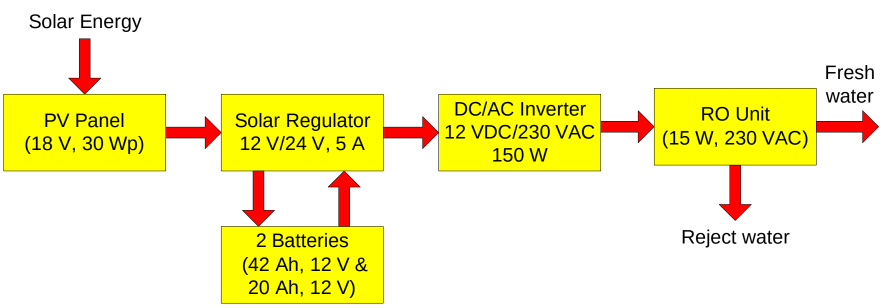

Fig. 10. Block diagram of the PV–RO system using battery storage.

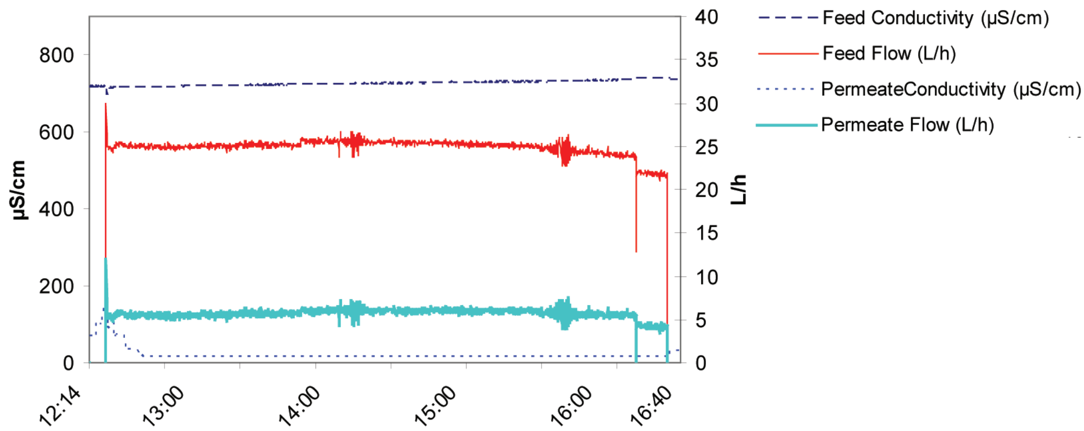

Fig. 11. Performance of the system (8 March 2007).

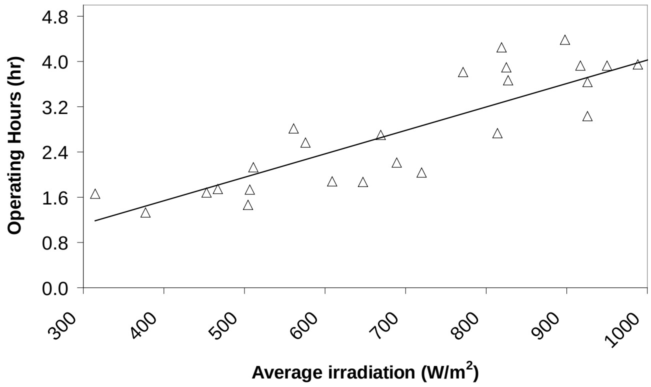

Fig. 12. Operating hours as a function of average solar irradiation.

Table 2
Summary of the cost results for the laboratory household PV–RO systems

Item	Battery household	Battery-less household
Total capital investment, $	1079	1055
Annual fixed charges, $/y	140	137
Annual membrane replacement, $/y	8	13
O&M annual payment, $/y	28	27
Total annual payment, $/y	176	177
Unit product cost, $/m^3	13	10
Unit product cost with blending, $/m^3	5.3	4

- Average specific energy consumption: 1.3 kWh/m^3 for battery-less based and 2.7 kWh/m^3 for battery based.

Based on the calculations, the estimated costs of water produced by the household PV–RO systems ranged form $10/m^3 for the battery-less based system to $13/m^3 for the battery based system. Further decrease in cost may be achieved by blending permeate with feed water.

4. Conclusions

This paper has presented the performance of a photovoltaic-powered household RO unit under different operating conditions. The system was tested at the laboratories of the Jordan University of Science and Technology with two alternatives of the system configuration, with and without storage batteries. Without batteries the rate of production of fresh water varied throughout the day according to the available solar power, but was steady when operated with batteries. The battery system produced 50 L of fresh water per day with an approximate permeate concentration of 13 mg/L. While the battery-less system produced 67 L/d with 16.5 mg/L of salt concentration. The specific energy consumption ranged from 1.1 kWh/m^3 to 4.3 kWh/m^3 for the battery system and ranged from 1.1 kWh/m^3 to 1.5 kWh/m^3 for the battery-less system. The cost of water produced from the battery-less system was 10 $/m^3 and was 13 $/m^3 for the battery based system.

Acknowledgment

The financial support of the Deanship of Research at the Jordan University of Science and Technology is highly appreciated.

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