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A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems — a technical and economical experimental comparative study

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Abstract

Photovoltaic powered brackish water reverse osmosis (PV-BWRO) desalination systems have been proved to be a technically and economically mature choice for water supply in isolated communities and islands suffering from lack or poor water quality. However, photovoltaic seawater reverse osmosis (PV-SWRO) systems are characterized for their high water production cost that reaches the value of 15–20 €/m^3. This high water production cost is mainly due to the high energy requirements (10–20 kWh/m^3) that accounts for around 60–70% of the operating and maintenance cost and that is due to the fact that majority of the small autonomous PV-SWRO do not contain energy recovery devices (ERDs). Another reason for the high water production cost is the need of solar batteries to achieve a constant pressure and flow rate for the membranes. Solar batteries are characterized by their high capital cost that reaches 110 €/kWh and operating cost mainly due to the replacement cost, solar batteries also have short operation life especially in hot climates.

In this work a batteryless PV-SWRO equipped with an ERD is installed, tested and compared to a battery based system, promising to produce 0.35 m^3/d in winter (feed water temperature 18°C) consuming only 4.6 kWh/m^3 with a cost of 7.8 €/m^3.

Keywords: Energy recovery; Seawater reverse osmosis; Specific energy consumption; Direct coupled

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1. Introduction

Water deficit and/or scarcity are serious problems in many areas of the world, such as the Middle East and North Africa countries (MENA), the southern European Mediterranean Islands (SEMI) and isolated communities in deserts. A small-scale, solar desalination system is applicable to areas that have (a) water supply problems; (b) no access to the electricity grid; and (c) ample solar resources [1]. Fortunately, all MENA countries, SEMI and deserts areas have an abundant solar energy potential that enhances the application of photovoltaic technology (PV) for powering small-scale reverse osmosis desalination units.

Photovoltaic powered reverse osmosis (PV-RO) systems are a proven technology due to the low specific energy consumption, relatively low maintenance requirements and the economic viability for desalting small amounts of water.

Small-scale seawater reverse osmosis (SWRO) systems without energy recovery devices (ERDs) exhibit high specific energy consumption that reaches values as high as 20 kWh/m^3 [2]. The desalinated product water cost increases with the increase of the operating and maintenance cost which consists of up to 70% energy consumption cost. Despite the fact that solar batteries provide constant flow and pressure the membranes, they are a problematic part of the system and have a reduced life especially in hot climates.

This paper presents laboratory experimental results of a direct coupled PV-SWRO desalination system without batteries equipped with a hydraulic energy recovery device of the Clark pump type compared against battery based system. The specific energy consumption of this system has been experimentally found to be in the range of 4–4.5 kWh/m^3 in both configurations.

2. General system description

The SWRO desalination unit is described in detail in reference [3], generally it consists of two 25–40 inch spiral wound seawater Filmtec membrane modules. A feed water positive displacement rotary vane pump pressurizes the NaCl solution (50 mS/cm), from the main mixing tank to one of the two cylinders of the Clark pump. The high-pressure brine enters the second Clark pump cylinder and exchanges its hydraulic energy with the medium feed water pressure (13 bar); the result of these actions is the intensification of the feed water pressure to the required membrane pressure (around 50 bar). The rotary pump is directly connected to a permanent magnet brushless DC motor with maximum power of 510 W. The DC power is produced from a PV array that consists of 18 Arco Solar PV panels of total peak power of 850 W that is connected to the DC motor either directly or via charge controller and a 315 Ah battery bank. The PV panels and the charge controller characteristics are described in Table 1.

Table 1
Detailed system configuration

Description	Characteristic value
PV module	Arco solar
Peak power (P_{mpp})	47 W
Peak power voltage (V_{mpp})	14.2 V
Open circuit voltage (V_{oc})	22 V
Short circuit current (I_{sc})	3.49 A
Normal operating cell temperature	45°C
Number of modules in series	2
Number of modules in parallels	9
Total number of panels	18
Charge controller	Tarom 235
System voltage	24 V
Nominal load current	35 A
Nominal discharge current	35 A
Max. current for 10 s	45 A
Surge current for 0.5 s	58 A

3. Battery based system performance

The system was tested for about ten consecutive days of November. The aim of the system testing was to investigate the water production quantity and quality as well as the specific energy consumption of the unit under constant feed pressure and flow. A representative day is analyzed below.

3.1. Available solar energy

The available solar energy and the corresponding PV power production can be seen in Fig. 1. The total available solar energy was recorded in Athens on the 11th of November to be 4.6 kWh/m^2/d, and the corresponding PV energy production was measured to be 2.9 kWh/m^2. Taking into consideration that the total PV area is 7.13 m^2 hence the solar energy transformed to electricity can be calculated to be around 8.8% which is a very logical value for a 10 years old monocrystaline PV panels working at solar irradiance of the half value of that of the test conditions (1000 W/m^2).

3.2. Water production and energy consumption

The system starts operation at 13:00 h when the battery voltage reaches the pre-selected voltage in the charge controller (26 V), as can be shown in Figs. 2 and 3. The RO unit produces a total amount of water production equal to 0.6 m^3/d for about 7 h of operation, at an average membrane pressure of 50 bar. The DC motor consumes around 2.6 kWh/d, hence the specific energy consumption can be calculated to be 4.3 kWh/m^3. The product water quality was measured to be within an average of 350 µS/cm.

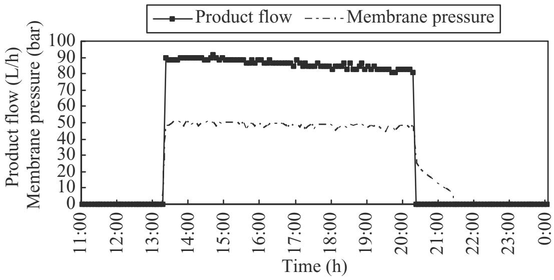

Fig. 2. Membrane pressure and product flow.

4. Direct coupled system

In this configuration the PV array was directly connected to the DC motor and the total system performance was recorded for one week on November 2006. The aim of the direct connection was to investigate the RO system under variable pressure and flow. The main advantage of this configuration is the simplicity of the system since

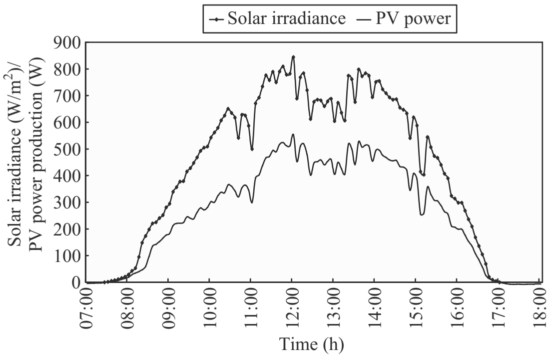

Fig. 1. Solar irradiance and the corresponding PV power.

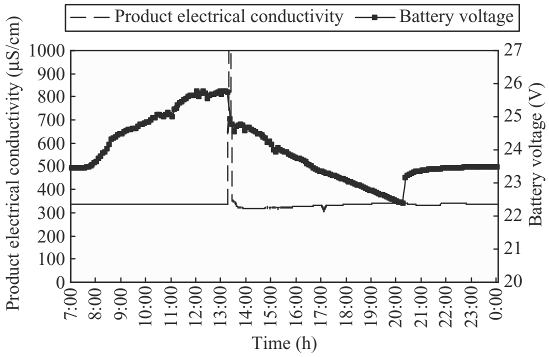

Fig. 3. Battery voltage and product quality.

it does not contain batteries or charge controller and as a result it has lower capital investment cost and less environmental effects due to the lead acid batteries replacement. The system performance under variable conditions is discussed below.

4.1. Available solar irradiance

Fig. 4 represents the available solar irradiance in Athens at the 25th day of November 2006 and the corresponding PV energy production. The total solar energy was measured to be 4.1 kWh/m^2/d and the corresponding PV daily energy production 1.6 kWh/d. The solar energy transformed to electricity at this configuration was calculated to be 5.5% which is lower than that of the battery based system due to the power mismatch between the PV array and the DC motor.

4.2. Water production and energy consumption

As can be shown in Fig. 5 the product water production starts at 9:10 h and continues with variable production till 15:10 h producing total product amount of 0.35 m^3/d. The membrane pressure at which the system starts to produce acceptable water quality (less than 1000 μS/cm), see Figs. 5 and 6, was recorded to be 37 bar at 9:40 h. Despite the intermittent conditions of flow and pressure, the average product conductivity was recorded to be 390 μS/cm. The total energy consumed by the DC motor was calculated from the consumed current and voltage to be 1.6 kWh/d, hence the specific energy consumption at this configuration was found to be 4.6 kWh/m^3, which is slightly higher than that of the battery based system (4.3 kWh/m^3).

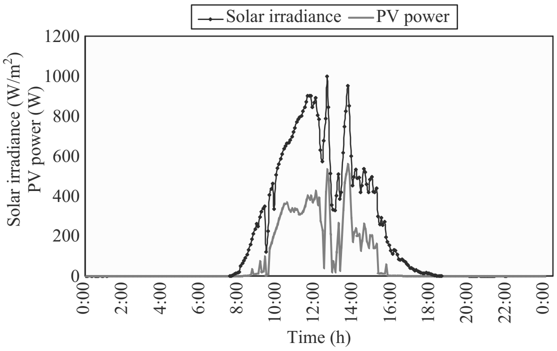

Fig. 4. The available solar energy and the corresponding PV power.

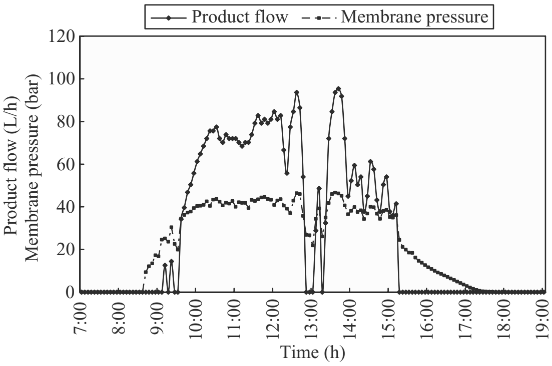

Fig. 5. Product flow and membrane pressure.

5. Water production cost

The water production cost was calculated in each of the two configurations using the Life Cycle Cost method (LCC). In Table 2, the several economic parameters of the system are analyzed.

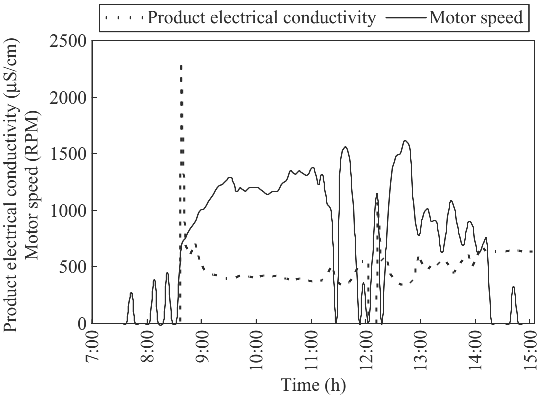

Fig. 6. Motor speed and product quality.

Table 2
Economic parameters of the system

	Battery based system	Direct coupled system
Total capital investment (€)	19,500	18,000
Annualized cost (€/year)	2640	2330
Annual energy production (kWh/year)	1380	1380
Specific energy consumption (kWh/m^3)	4.3	4.6
Annual water production (m^3/year)	321	300
Product quality (µS/cm)	350	390
Water production cost (€/m^3)	8.3	7.8

The economic analysis has been performed under the following assumptions:

- Interest rate 5%
- Economic life of batteries 5 years and for membranes 4 years.
- The two configurations are assumed to operate under the same energy production from the PV.

6. Results discussion

The results obtained from this comparative experimental study can be summarized in Table 3.

From Table 3, some conclusions can be drawn as follows:

- The PV system has a higher efficiency with the battery based system. This fact leads to the conclusion that in battery based systems, the PV array size could be smaller than that of the direct coupled systems.
- There was no big difference in the specific energy consumption, only 3.7% excess energy consumption in the direct coupled configuration.
- For a specific available solar energy the battery based system produces only 6.5% more product water.
- The addition of a small battery bank and a charge controller is not economically justified due to the high replacement cost of the battery and the high capital cost of small battery bank that reaches the value of 300 €/kWh while it is around 150 €/kWh for large battery banks.

Table 3
Results summary

	Battery based system	Direct coupled system
Available solar energy (kWh/d)	32.8	29.2
PV energy production (kWh/d)	2.9	1.6
DC motor energy consumption (kWh/d)	2.6	1.6
Solar energy transformed to electricity (%)	8.8	5.5
Total product (m^3/d)	0.6	0.35
Specific energy consumption (kWh/m^3)	4.3	4.6
Annual water production for the same amount of DC energy consumption (m^3/year)	321	300
Product quality (µS/cm)	350	390
Water production cost (€/m^3)	8.00	7.8
Total system efficiency (motor energy/solar energy) (%)	8	5.5

- A large battery bank (>1500 Ah) could improve the system behavior, but will increase the environmental effects and operating cost that might be very high in isolated areas.

7. Conclusions

A direct coupled PV-SWRO was experimentally analyzed toward a battery based system. Using a small battery bank in such a small desalination bank was not economically justified due to the high capital, maintenance and replacement cost. The water production cost (7.8 €/m^3) compares well with the available water cost in the Agean Greek Islands.

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