10-2010

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Ali Al-Karaghouli
National Renewable Energy Laboratory

Lawrence L. Kazmerski
National Renewable Energy Laboratory

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Preprint

Ali Al-Karaghouli and Lawrence L. Kazmerski
National Renewable Energy Laboratory

To be presented at World Renewable Energy Congress XI
Abu Dhabi, United Arab Emirates
September 25-30, 2010

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5A00-48342
October 2010

Contract No. DE-AC36-08GO28308

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

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Economic Analysis of a Brackish Water Photovoltaic-Operated (BWRO-PV) Desalination System

Ali Al-Karaghouli* and Lawrence L. Kazmerski
National Renewable Energy Laboratory
Golden, Colorado 80401 (USA)
* Corresponding author: ali.al-qaraghuli@nrel.gov

Abstract

The photovoltaic (PV)-powered reverse-osmosis (RO) desalination system is considered one of the most promising technologies in producing fresh water from both brackish and sea water, especially for small systems located in remote areas. We analyze the economic viability of a small PV-operated RO system with a capacity of 5 m^3/day used to desalinate brackish water of 4000 ppm total dissolve solids, which is proposed to be installed in a remote area of the Babylon governorate in the middle of Iraq; this area possesses excellent insolation throughout the year. Our analysis predicts very good economic and environmental benefits of using this system. The lowest cost of fresh water achieved from using this system is US \$3.98/ m^3, which is very reasonable compared with the water cost reported by small-sized desalination plants installed in rural areas in other parts of the world. Our analysis shows that using this small system will prevent the release annually of 8,170 kg of CO_2, 20.2 kg of CO, 2.23 kg of CH, 1.52 kg of particulate matter, 16.41 kg of SO_2, and 180 kg of NOx.

Keywords: water desalination, PV system, economic analysis, greenhouse gases reduction, remote area.

1. Introduction

Combining renewable energy systems with reverse-osmosis (RO) water desalination offers a viable solution to the scarcity of water in remote areas, especially in regions characterized by plentiful solar radiation such as the middle of Iraq. The main desirable features for these combined systems are low cost (when the site is far enough from the grid), low maintenance requirements, simple operation, very high reliability, and suitability for both sea and brackish water.

Brackish water photovoltaic-operated desalination systems (BWPV-RO) use a standard RO system, but are powered by batteries charged by PV arrays. Batteries used in PV-RO systems keep a constant flow for 24 hours a day, thus maximizing the production and they make use of the invested capital. They also maintain the quality of the produced water and help in managing membrane fouling. Without batteries (to reduce system capital cost), the power available from a PV array varies with the intensity of sunshine; to make the best use of this available power, a connected RO system must also operate at variable power. Again, this is contrary to the normal operation of mainstream RO systems. The efficiency of the RO system must be maintained over a broad range of operating power; this is particularly challenging in the balance of the plant. Numerous desalination plants using a PV-RO system with and without batteries have been implemented in different parts of the world [1].

In this work, the BWPV-RO system were analyzed economically by using HOMER software program developed by the U.S National Renewable Energy Laboratory [2] and information from Pure Aqua for water treatment and reverse osmosis company [3].

2. RO System Selection

In an RO system, water analysis is required before selecting a system. Based on the water analysis, one can determine the pre-filtration required before the RO unit. In addition, the water analysis will determine the type, number, and configuration of membranes, as well as the pumps and motors. The pre-treated feed water is forced by a high-pressure pump to flow across the membrane. The desalted water (permeate water) passes through the membrane, whereas the majority of the dissolved solids is rejected from the membrane as high-pressure brine. Brackish-water RO systems usually operate at a higher (water) recovery ratio than seawater systems. Thus, the proportion of the energy in the concentrate is lower and the importance of brine-stream energy recovery is reduced. Post-treatment is necessary before the water end-use. Figure 1 shows a schematic diagram of a BWRO unit.

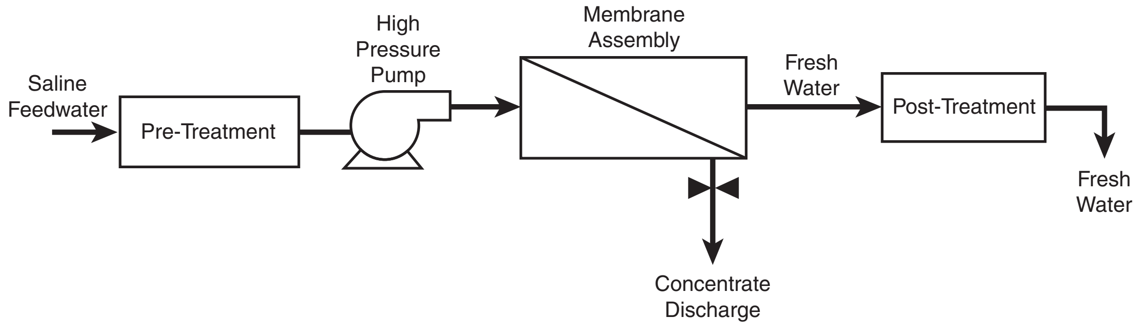


Figure 1. Schematic diagram of a BWRO unit.

3. HOMER Input Data

The solar radiation data for the Babylon governorate in the middle of Iraq (32° 29" N latitude and 45° 28" E longitude) were obtained from the NASA surface meteorology and solar energy Web site [4]. The annual average solar radiation for this region is 5.52 kWh/m^2/day. Figure 2 shows the site solar resource profile over a 1-year period. The proposed PV system used to power the RO units, which will be analyzed by HOMER, consists of PV modules, batteries, charge controller, inverter, auxiliary diesel generator, and the rest of the balance-of-systems (i.e., modules structure, wiring, fuses, and other system safety devices). The prices for the PV system devices were taken from the Solarbuzz Company report [5] for solar energy electricity.

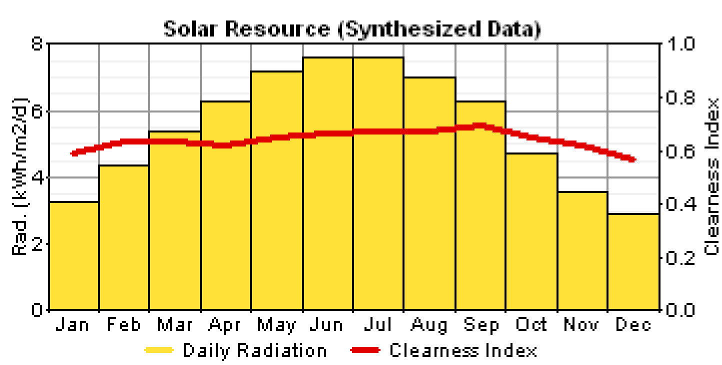


Figure 2. Monthly average solar radiation and clearance index.

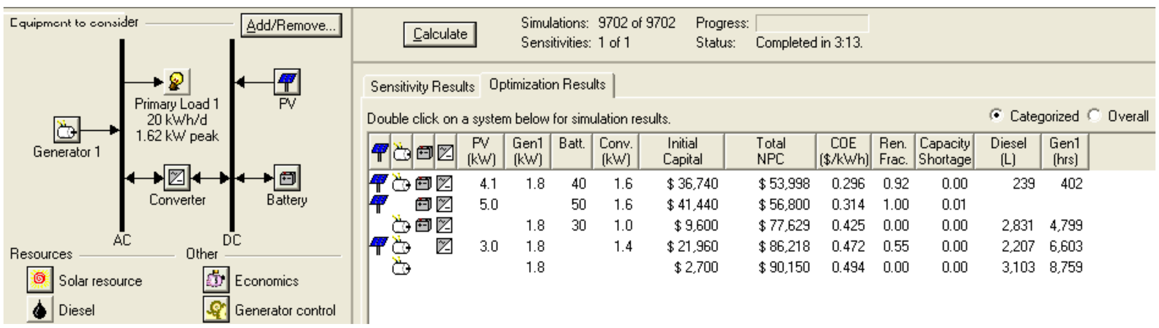
4. HOMER Optimization Analysis

In HOMER, the best possible or optimal system configuration is the one that satisfies the user-specified constrains at the lowest total net present cost (NPC) [2]. In this analysis, to supply 5 m^3/day of fresh water using an RO/PV system, we considered two cases:

A. BWRO-1500 unit/PV system running 24 hours per day
B. BWRO-6000 unit/PV system running 6 hours per day.

For case A, the RO unit daily load and peak wattage was found to be 20 kWh/day and 1.62 kW, respectively [3]. At a diesel fuel price of US$0.4/liter and 0% interest rate (I.R.), the results of the HOMER analysis show that the optimum PV system comprises 4.1 kW of PV modules, a 1.6-kW inverter, 40 batteries (6 V and 25 Ah each), and a 1.8-kW auxiliary diesel generator. The total system NPC is US$53,988, and the cost of electricity produced is US$0.296/kWh. When using the PV system only, the system comprises 5 kW of PV modules, a 1.6-kW inverter, and 50 batteries (6 V and 325 Ah each). The total NPC is US$56,800, and the cost of electricity produced is US$0.314/kWh. When using a diesel generator only, a 1.8-kW unit is required, and the system NPC is US$90,150 and electricity production cost is US$0.494/kWh. Table 1 shows the HOMER optimization results for this case.

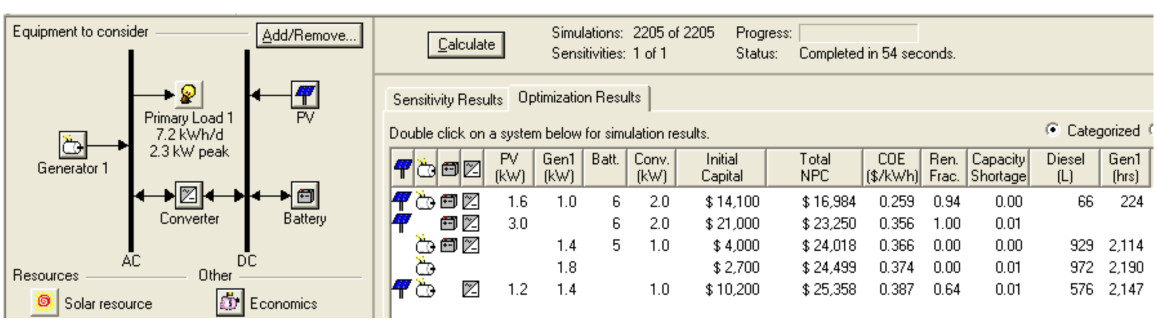
Table 1. HOMER optimization results for case A at 0% interest rate and US $0.4/L of diesel



PV (kW)	Gen1 (kW)	Batt.	Conv. (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)
4.1	1.8	40	1.6	$ 36,740	$ 53,998	0.296	0.92	0.00	239	402
5.0		50	1.6	$ 41,440	$ 56,800	0.314	1.00	0.01		
	1.8	30	1.0	$ 9,600	$ 77,629	0.425	0.00	0.00	2,831	4,799
3.0	1.8		1.4	$ 21,960	$ 86,218	0.472	0.55	0.00	2,207	6,603
	1.8			$ 2,700	$ 90,150	0.494	0.00	0.00	3,103	8,759

For case B, the RO unit daily load and peak wattage was found to be 7.2 kWh/day and 2.3 kW peak, respectively [3]. At a diesel fuel price of US$0.4/liter and at 0% interest rate, the results of the HOMER analysis show that the optimum PV system comprises 1.6 kW of PV modules, a 2.0-kW inverter, 6 batteries (6 V and 325 Ah each), and a 1.0-kW diesel generator. The total system NPC is US$16,984 and the cost of produced electricity is US$0.259/kWh. When using a PV system only, the system comprises 3 kW of PV modules, a 2.0-kW inverter, and 6 batteries (6 V and 325 Ah each). The total NPC is US$23,250 and the cost of electricity produced is US$0.356/kWh. When using a diesel generator only, a 1.8-kW unit is required, and the system NPC is US$24,499 and the electricity production cost is US$0.374/kWh. Table 2 shows the HOMER optimization results for this case.

Table 2. HOMER simulation result for case B at 0% interest rate and US $0.4/L diesel fuel



PV (kW)	Gen1 (kW)	Batt.	Conv. (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)
1.6	1.0	6	2.0	$ 14,100	$ 16,984	0.259	0.94	0.00	66	224
3.0		6	2.0	$ 21,000	$ 23,250	0.356	1.00	0.01		
	1.4	5	1.0	$ 4,000	$ 24,018	0.366	0.00	0.00	929	2,114
	1.8			$ 2,700	$ 24,499	0.374	0.00	0.01	972	2,190
1.2	1.4		1.0	$ 10,200	$ 25,358	0.387	0.64	0.01	576	2,147

To study the effect interest rate and the change in fuel price, we considered an I.R. of 6% and a fuel price of US$1.0/liter. Table 3 shows the change in electricity production cost for the three systems due to the change in I.R. and fuel price.

Table 3. Cost of electricity for the three systems and both types of units

Electricity Production Cost (US$/kWh)												
	PV System and Auxiliary Generator				PV System Only				Generator Only			
	RO-1500 unit 24 h/day load		RO-6000 unit 6 h/day load		RO-1500 unit 24 h/day load		RO-6000 unit 6 h/day load		RO-1500 unit 24 h/day load		RO-6000 unit 24 h/day load	
I.R.	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L
0%	0.296	0.309	0.259	0.273	0.314	0.314	0.356	0.356	0.494	0.749	0.374	0.596
6%	0.445	0.503	0.426	0.489	0.532	0.532	0.663	0.663	0.512	0.767	0.412	0.636

5. Water Production Cost

Several parameters have a large impact on the price of the permeate water produced by an RO unit. These parameters include the following:

1. Initial cost of the unit
2. Installation cost of the unit
3. Cost of electricity or fuel needed to operate the unit
4. Operation cost of the unit
5. Membranes and filters replacement cost
6. Maintenance and repair cost.

The cost of produced water is found by calculating the lifetime system cost (i.e., initial, operation, replacement, and maintenance costs) divided by the amount of water in m^3 produced during the lifetime of the RO unit. The initial and other costs (20-year lifetime) for the RO units are taken from the Pure Aqua Company's information on water treatment and reverse osmosis (Table 4), and HOMER calculated the cost of electricity or fuel needed to run these units. Table 5 shows the estimated price of the fresh water produced.

Table 4. RO capital and operating cost

Item	RO-1500 Unit (US$)	RO-6000 Unit (US$)
1. Initial and installation cost	10,000	15,000
2. Operation labor cost	62,940	62,940
3. Membrane cost	5,000 (1 every 2 years)	20,000 (4 every 2 years)

Table 5. Cost of fresh water for the three systems and both types of load

Water Production Cost (US$/$m^3$)												
	PV System and Auxiliary Generator				PV System Only				Generator Only			
	RO-1500 unit 24 h/day load		RO-6000 unit 6 h/day load		RO-1500 unit 24 h/day load		RO-6000 unit 6 h/day load		RO-1500 unit 24 h/day load		RO-6000 unit 24 h/day load	
I.R.	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L	$0.4/L	$1.0/L
0%	3.98	4.04	4.43	4.49	4.06	4.06	4.82	4.82	4.80	5.80	4.89	5.78
6%	5.14	5.38	5.67	5.91	5.49	5.49	6.61	6.61	5.40	6.42	5.61	6.48

The cheapest price is found to be US$3.98 per m^3 of fresh water at 500ppm produced by the RO-500 unit operated by a PV system and auxiliary generator at diesel price of US$0.4/L and 0% I.R. If it is difficult to provide diesel and adequate maintenance to the generator in a remote area, then the second choice is to use PV system only to run the RO unit. The price of the fresh water produced from this system is US$4.06 which is still a reasonable price compared to water price we could get by using a diesel generator alone in remote areas. The cost of the produced fresh water is shown in table5.

6. Environmental Benefits of Using PV-Operated RO System

Our HOMER software analysis calculated the reduced amounts of greenhouse gases (GHG) and found that a significant annual reduction is achieved using this small system, as presented in Table 6.

Table 6. GHG emission reduction

Pollutant	CO_2	CO	Hydrocarbon	Particulate Matter	SO_2	NO_X
Emission (kg/yr)	8,170	20.2	2.23	1.52	16.41	180

7. Conclusion

We used HOMER software to find the optimum power system to run two types of small RO units to desalinate brackish water (from 4000 to 500 ppm total dissolved solids). One of these units runs for 24 hours per day (RO-1500), and the other runs for 6 hours per day (RO-6000) to produce the same amount of fresh water (5 m^3/day). The results show that the optimum system uses a PV system with an auxiliary diesel generator for both types of RO units. The PV system NPC, the cost of electricity produced to run the RO-1500 unit and the cost of the fresh water produced from this unit is found to be US$53,998, US$0.296/kWh, and US$3.98/$m^3$ respectively. For the RO-6000 unit, we found the PV system NPC, cost of electricity, and cost of fresh water produced to be US$16,998, US$0.259/kWh, and US$4.43/$m^3$, respectively. The cost of the produced water is very reasonable compared to the cost of water produced by desalination plants installed in remote areas in other parts of the world. The environmental benefits of using the PV system are also significant, as shown in Table 11. The results of this study show the economic feasibility and advantage of using this type of system in remote areas.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
October 2010	Conference Paper	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Economic Analysis of a Brackish Water Photovoltaic-Operated (BWRO-PV) Desalination System: Preprint	DE-AC36-08GO28308
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
A. Karaghouli and L. Kazmerski	NREL/CP-5A00-48342
	5e. TASK NUMBER
	5A01.1001
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	NREL/CP-5A00-48342
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS

water desalination; PV system; economic analysis; greenhouse gases reduction; remote area

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER *(Include area code)*

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Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)