Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.846496

(2013) 1–10

Taylor & Francis
Taylor & Francis Group

Techno-economic evaluation of a small-scale PV-BWRO system at different latitudes

P. Poovanaesvaran, M.A. Alghoul*, Assim Fadhil, M.M. Abdul-Majeed, Nilofar Assim, K. Sopian

Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
Email: dr.alghoul@gmail.com

Received 17 June 2013; Accepted 1 July 2013

ABSTRACT

Water scarcity is a problem in remote locations, and producing fresh water in remote areas is an expensive process. The objective is to evaluate the optimum PV system to power BWRO desalination system that can produce 60 m^3/d at constant daily load profile for locations at different latitudes ranging from 60°S to 60°N worldwide. Different design configurations are simulated using ROSA software. Simulations showed that two-stage RO system is the better option with lower energy consumption. Hybrid optimization model for electric renewables (HOMER) is used to evaluate a range of equipment and design options over varying constraints and sensitivities in terms of sizing for the economic optimization of the PV power system. The minimum initial cost of the PV system is $102,000 and found at latitudes 50° S/N, while the maximum initial cost is $133,000 and found at latitude −60°. The economic performance of the PV system is then optimized under Malaysia latitude by allowing portions of the annual load to go unserved. The result shows that the optimum combination is a system with a 28 kW PV array, 76 batteries, and 12 kW converter with 1.5% annual unmet load fraction at 2° of PV slope. Allowing a small percentage of loads to go unserved throughout the year reduces the cost of the system. Powering RO system with PV power showed different initial cost for different latitudes.

Keywords: Desalination; Small-scale PV-BWRO; ROSA; HOMER; Techno-economic; Locations of different latitudes

1. Introduction

Monsoon rains visit Malaysia about twice a year. However, fresh water remains a scarcity in remote locations in the country. Desalination provides a solution for residents in remote areas to enjoy better living standards, as clean water is one of the most important needs for survival and good health.

*Corresponding author.

The most widely used methods for desalination include thermal process and membrane process. Reverse osmosis (RO) falls under the membrane process category. In RO, most of the energy is used for the initial pressurization of the feed water. The initial pressurization for brackish water reaches up to 27 bar, whereas that for seawater desalination reaches up to 70 bar [1]. RO systems are very flexible in feed water quantity and quality, as well as in the site location and the start-up and shut-off of the system [2,3]. In addition, RO systems are constructed in a modular manner that can adopt a renewable energy supply [2]. Factors such as the daily per capita consumption, total population, as well as hours of operation of the unit per day are critical factors for the sizing of the RO unit [4].

Water characterization is the first step in designing an RO system. El-Manharawy et al. [5] discussed in detail about water characterization and guidelines for RO system design. The type of membrane and its arrangement are determined based on feed water characterization. Reverse osmosis system analysis (ROSA) [6] is used to design the optimum RO system that can produce 60 m^3 of fresh water per day with total dissolved solids (TDS) of 10,000 mg/l.

Stand-alone photovoltaic (PV) systems provide a pollutant-free and cost-effective solution for remote areas. A PV system produces energy by directly converting sunlight into electrical energy through a process called the photovoltaic effect. When sunlight strikes a PV system, it frees the electrons to move, producing electricity. Electricity produced by a PV system is direct, simple, maintenance-free, quiet, clean, renewable, and economical for use in rural areas [7]. Currently, electricity produced by a PV system is already cost-competitive, and the price is falling continuously. Solar energy is the world's most abundant source of energy and is one of the most popular alternative energy sources.

This paper discusses the design of a stand-alone PV system for an optimized brackish water reverse osmosis (BWRO) system that provides drinking water for a small village in a remote area in Malaysia. The discussion includes load profiles, sizing of the stand-alone PV system for supplying electrical load to the BWRO system, and economic estimation of the system.

The National Renewable Energy Laboratory [8] designed a hybrid optimization model for electric renewables (HOMER), a type of software for evaluating a range of equipment options on sizing and optimization of system over varying constraints. The current study adopts this tool for simulations and analyses. Electrical loads, solar resources, economic constraints, control methods, component types, number of components, costs, and efficiency and lifetime values are fed into HOMER for analysis. HOMER provides the best option based on modeling and investigates all possible scenarios by sorting the feasible case in order of increasing net present value. The cost includes component replacement, operation and maintenance. Sensitivity analysis repeats the evaluation on a range of values based on user-defined factors, such as load size, reliability requirement, and resource quality.

2. BWRO system

Osmosis is defined as the net movement of water from an area of lower concentration to that of higher concentration across a partially permeable membrane. If excess pressure is applied on the higher concentration, the process is reversed through RO. In RO, water moves from an area of higher concentration to that of lower concentration.

The RO process starts with saline water (feed) being pumped into a closed vessel where saline water is pressurized against the membrane (Fig. 1). Water molecules pass through the membrane, thereby, increasing the concentration of the reject water and producing purified water on the other side. Initial pressurization of the feed water consumes a large share of the energy consumption [9]. Other factors that influence the energy consumption of RO are membrane properties and salinity of the feed water [10,11]. High water salinity requires more energy to overcome the osmotic pressure. Initial pressurization for brackish water ranges from 250 psi to 400 psi [1]. BWRO plants have recovery rates of as high as 90%.

Gocht et al. [12] investigated the technical feasibility and cost benefit of a PV-powered brackish water small-scale desalination plant in a rural area. They revealed the socio-economic feasibility of desalination that is provided by a transient, discontinuously operated, PV-coupled RO system. In general, continuous operation is defined as 24-h daily operation, whereas discontinuous operation pertains to operation for 5–10 h a day, depending on the location and need for optimum operating hours. Continuous operating systems require large battery banks to provide power at night or during cloudy times; this requirement increases the cost. Another option is to store water in a storage tank to reduce the cost and number of batteries needed [13].

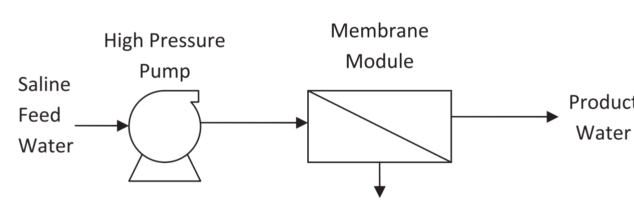

Fig. 1. Single-stage module arrangement.

2.1. Design of the BWRO system

Module arrangement is an important part of designing an RO system. It is determined by feed water composition, product water quality, and the product flow needed. Researchers in brackish water systems use a variety of arrangements to optimize the performance of RO systems. Membrane configuration and feed water salinity influence the energy requirement of the RO system [14–16]. Feed pressure should be operated close to the osmotic pressure of the exit to the brine chamber to enable operation at minimum energy consumption [17]. This setup is achievable as current brackish water membranes have high permeability [18]. Another way to achieve energy-optimal operation that is very close to the theoretically predicted energy consumption is by implementing an optimization-based control system [19]. Various mixing approaches reduce energy consumption, but do not provide an advantage in energy use reduction [20]. The choice of configuration includes single-stage, two-stage, and two-pass.

A simple single-stage module arrangement is shown in Fig. 1 [9]. Feed water is pumped into the RO module at a pressure designated by the high pressure pump. It then splits into product water and reject water [21]. As efficiency is independent of water recovery and generated feed pressure, optimal water recovery is not influenced by the efficiency of the high pressure pump; however, specific energy consumption increases with decreasing pump efficiency [22].

The module arrangement shown in Fig. 2 is a single-stage RO system with an energy recovery device (ERD). An ERD reduces the energy consumption of RO systems [9]. It reduces the optimal minimum energy location to lower recoveries [22]. ERD can reduce the energy consumption and operating cost of the system, however, its initial cost of installation is high.

The two-pass RO system can provide product water with very low salinity (Fig. 3). It is suitable for feed water with very high salinity. The pressure of the product water after the first pass is lower than the osmotic pressure of the second stage. By including a pressure pump in the system, pressure can be increased from atmospheric pressure to pressure between 20 and 40 bar. The second pass is operated at high average permeation flux with recovery rates from 85% to 90% due to very low concentration of suspended particles and dissolved salts [23].

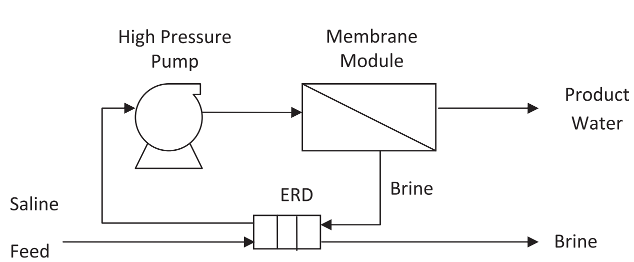

Fig. 2. Single-stage module arrangement energy recovery device.

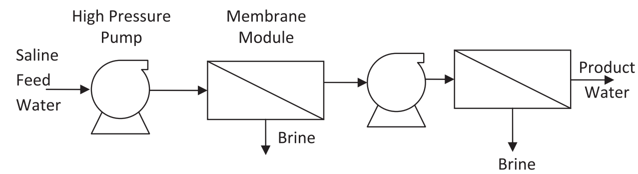

Fig. 3. Two-pass RO system.

A two-stage RO system with optional inter-stage pump is shown in Fig. 4. The inter-stage pump increases the feed pressure from the first module before the feed enters the second module. The inter-stage pump is optional and is needed when the pressure to the second stage cannot be met using a single-feed pump [24]. With an inter-stage pump, the feed water pressure and water flux is increased to an optimum value, and the second stage can be operated in nominal hydraulic conditions [21]. Two-stage is more energy-efficient relative to a single-stage system, at the expense of a wider membrane surface area [24]. Designing an optimum RO system must consider both the cost of energy and the size of the membrane area. Different design configurations may be simulated by using ROSA [6]. Simulation shows that the two-stage RO system is the better option for its lower energy consumption (Fig. 5).

2.2. Cost of the BWRO system

The two-stage RO system is made of 8″ by 40″ BW30HR-440i RO membrane elements (DOW Filmtec), with each costing USD 630. The current setup uses 32 membranes, 16 at each stage, for a total cost of USD 20160. Each membrane is placed inside

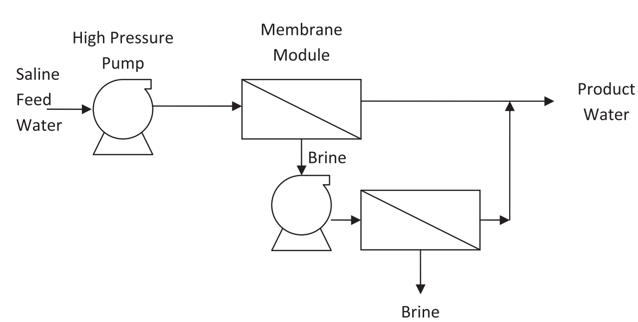

Fig. 4. Two-stage RO system with optional inter-stage pump.

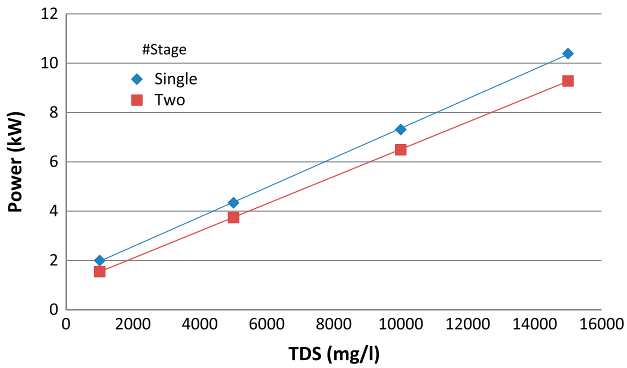

Fig. 5. Energy consumption for different feed water TDS values for single and two-stage RO systems.

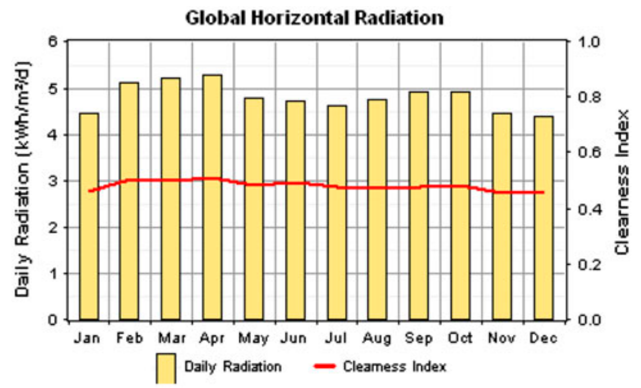

Fig. 6. Average daily radiation and clearness index for the site in Malaysia.

pressure vessels. The cost for the pressure vessel is USD 240. The total cost of 8 pressure vessels is USD 1920. The pump and water storage tank are priced USD 200 each. The total cost of the piping and stand is USD 200. The total cost of BWRO system is USD 22680 (Table 1). The prices are retail prices obtained from the Internet.

3. Stand-alone PV system sizing

The basic components of a PV system are PV arrays, controller, battery, and inverter. Sizing of the stand-alone PV system first involves estimation of the energy consumption of the BWRO system and the solar radiation at the location of operation.

3.1. Solar resource

The present structure uses solar resources for a site in Malaysia at 2°56′N and 105°47′E. Solar radiation data for this location are obtained from the NASA Surface Meteorology and Solar Energy website [25]. The annual average solar radiation for the selected location is 4.79 kWh/m^2/d. Fig. 6 shows the monthly solar resource profile over a year-long period. Rainfall range at the location is from 2,032 mm to 2,540 mm, and temperature is between 21 and 32 ℃. Relative humidity is 80–90%, and solar radiation is approximately 12–20 MJ/m^2.

HOMER [8] uses Graham Algorithm to generate statistically hourly solar radiation data. The calculations are based on the latitude and longitude of the location where the PV modules are installed, the direction of the PV modules, the slope of the PV modules relative to the horizontal standard, ground reflectance (the fraction of solar radiation incident of the ground that is reflected), and 12 average daily solar radiation values, one for each month.

3.2. Electrical load

The daily load profile of the BWRO system is illustrated in Fig. 7. The BWRO system operates 10 h/day from 8 am to 6 pm. The total annual average daily load is 66 kWh/d. The system is chosen to operate during daytime to minimize the number of batteries needed to operate the system. Excess water produced is stored in the storage tank for later consumption.

3.3. Effect of solar radiation budget on economic aspects

Real interest rate is equal to nominal interest rate minus the inflation rate. A real annual interest rate of

Table 1
Capital cost of building a BWRO system

Item	Unit price	Quantity	Total
RO membrane elements	630	32	20,160
Pressure vessels	240	8	1,920
Pump	200	1	200
Water storage tank	200	1	200
Others (building materials)			200
			22,680

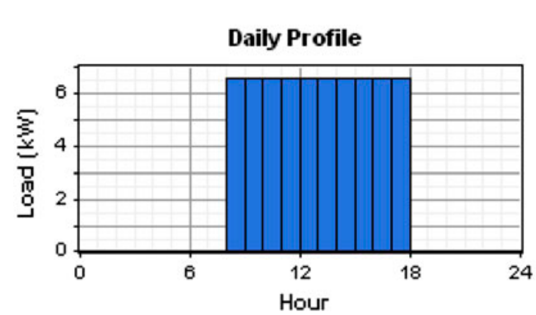

Fig. 7. Hourly load profile of the BWRO system.

6% is assumed in this study. The appropriate value of the interest rate depends on current macroeconomic conditions, financial strength of the implementing entity, and concessional financing or other policy incentives. HOMER [8] converts the capital cost of each component to an annualized cost by amortizing it over its component lifetime using the real discount rate. The lifetime of the project is assumed to be 25 years. The economic life of batteries is 10 years, that of the converter is 15 years, and that of the PV panels is 25 years. Fig. 8 shows comparison of initial cost of PV system at different latitude ranging from 60˚S to 60˚N at same longitude (105˚47′E) with an average daily load of 66 kWh/d. The angle is adjusted best based on their latitude.

3.4. Reliability constraint

The economic performance of the PV system can be improved significantly if a portion of the annual load is unserved. A PV system does not need to serve occasional large loads. The load is normally smaller than the regular load that must be served. Extreme cases of the peak load, such as after several cloudy days, rarely occur. The BWRO system is built with a storage tank that reserves water to be used during cloudy days. This setup allows a small fraction of loads to go unserved, thereby reducing the number of batteries needed and saving capital and operational costs. Typically, the maximum annual unserved load is between 0.5% and 3%.

3.5. Equipment

The BWRO load, converter, batteries, and PV arrays are among the equipment considered. Fig. 9 shows the proposed scheme implemented in HOMER. The list of system components and sizes that are considered for this analysis is outlined in Table 2. The

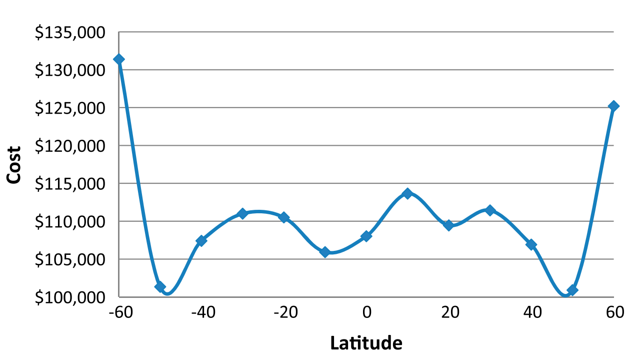

Fig. 8. Initial cost of PV system at different latitude at same longitude (105˚47′E).

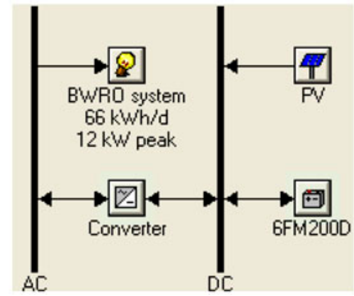

Fig. 9. PV-BWRO system setup on HOMER.

prices of the PV system devices are taken from the Solarbuzz website [26].

3.6. PV sizing

The capital and replacement costs of PV panels amount to USD 2.29/W. The cost includes shipping, tariffs, installation, and dealer mark-ups. Very little maintenance is needed for the panels. By placing the panels at an angle, rain would clean the dust and dirt from the surface of the panel. Thorough cleaning needs to be done every now and then depending on the cleanness and dirt accumulation on the panels.

3.7. Batteries

Batteries are included in the system analysis; they store energy for use during cloudy weather and for providing stable current supply to the system. Vision 6FM200D is chosen for its availability. Moreover, fewer batteries are needed as each can produce 12 V. The capital and replacement cost of one battery is USD 248.

Using battery as part of PV-BWRO makes the system more efficient and reduces energy consumption of the pumps [27]. This reduction is due to the fact that batteries can provide stable energy flow to the RO system [7]. A stable energy feed produces a stable flow of fresh water, thereby maximizing the output of RO system. A battery-based system reduces the size and cost of the PV-BWRO system as the size of the PV system used to power RO system can be dramatically reduced [27].

3.8. Converters

Power produced by PV modules is in DC form. It must be converted to AC in order to power the pumps. A power converter is used to achieve this. The installation and replacement cost of a power converter for 1 kW is USD 714. The efficiency of the inverters is assumed to be 85%.

Table 2
Summary of the system components considered

Component	Size	Capital cost (USD)	Replacement cost (USD)	O&M cost (USD)	Lifetime
PV panels	20–50 kW	2,290/kW	2,290/kW	0.00	25 years
Batteries: Vision 6FM200D	30–100 batteries	248/battery	248/battery	10.00/year	8 years
Converter	10–40 kW	714/kW	714/kW	100/year	15 years

4. Results and discussion

A PV system consists of PV arrays, batteries, a controller, an inverter, and the load. Its performance depends on several factors, especially meteorological conditions, such as solar radiation. The local condition of the load, irradiation, temperature, and their component characteristics must be determined when designing an efficient and economical PV system.

4.1. Unmet load

With regard to the unserved load in the HOMER [8] simulation, the threshold of the PV system becomes more cost-effective. Allocating some of the load as unserved throughout the year translates to normal sizing of the PV array and battery bank. However, the worst-case scenario of extended cloudy weather and occurrence of peak loads need to be taken into consideration. The BWRO system comes with storage tank where fresh water will be stored for later use. The storage of water allows a maximum annual capacity shortage of 1.5%.

The optimum combination is lowest excess electricity fraction, unmet load fraction, and levelized cost of energy with a high PV slope. The high PV slope helps in the cleaning of dirt and dust from the PV array surface by rain. Fig. 10 shows the surface plot of excess electricity fraction over the PV slope and annual capacity shortage, superimposed with the levelized cost of energy. At 1.5% maximum annual capacity shortage, the PV angle of 2˚ is optimal. For more than 1.5% maximum annual capacity shortage, the levelized cost of energy drops slightly. The levelized cost of energy and excess electricity fraction work conversely (Fig. 11); excess electricity fraction peaks at a PV slope of 2˚, whereas the levelized cost of energy is lowest at this angle. Beyond 3˚ of PV slope, the excess electricity fraction drops, whereas the levelized cost of energy increases. At PV of 11˚, the levelized cost of energy is at peak and drops gradually until 12˚ before increase again at higher angles.

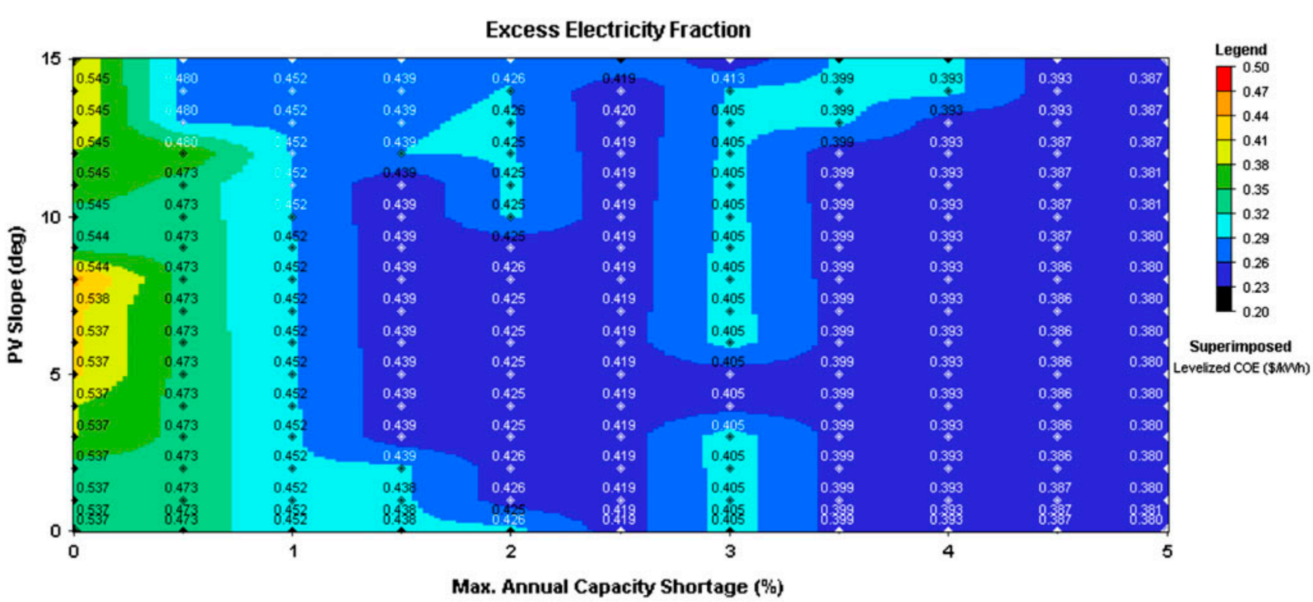

Fig. 10. Surface plot of excess electricity fraction over PV slope and annual capacity shortage with superimposed data on levelized cost of energy.

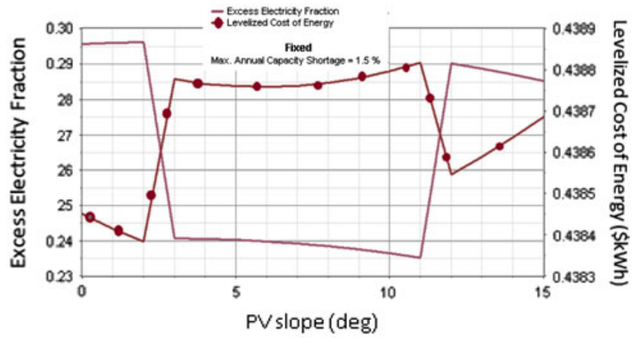

Fig. 11. Graph of excess electricity fraction and levelized cost of energy against PV slope at maximum annual capacity shortage of 1.5%.

4.2. PV slope

The optimum combination at 1.5% maximum annual capacity shortage with 2° of PV slope is 76 batteries and 28 kW PV array (Fig. 12). The general trend for increasing maximum capacity shortage shows drop in the number of batteries. The number of batteries and PV arrays decreases as the maximum annual capacity shortage increases. The number of batteries drops with the increase of shortage. Meanwhile, the number of PV array shows a small increase at shortage from 3%, but reduces for a larger shortage. The levelized cost of energy decreases with the increase in maximum annual capacity, whereas the unmet load fraction increases (Fig. 13). At 1.5% capacity shortage and 2° of PV slope, the levelized cost of energy is USD 0.438/kWh whereas the unmet load fraction is 0.01.

4.3. Sizing result

Fig. 14 shows the monthly average electrical production. According to HOMER simulation, the

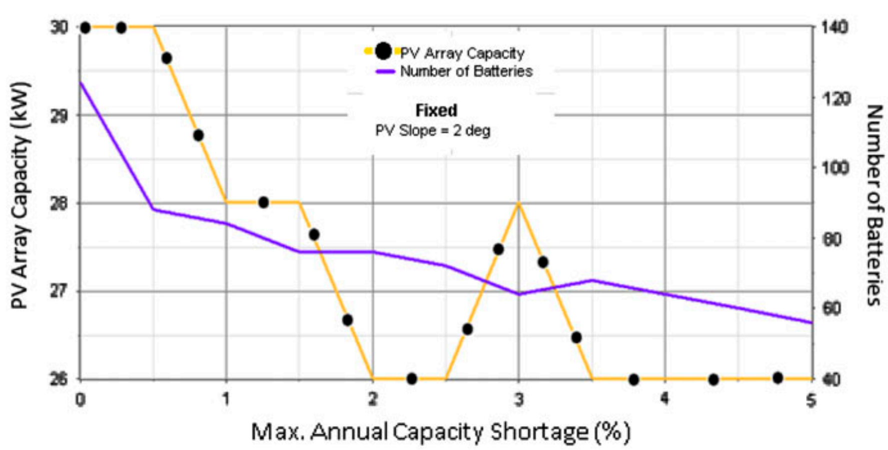

Fig. 12. Graph of PV array capacity and number of batteries against maximum annual capacity shortage at 2° PV slope.

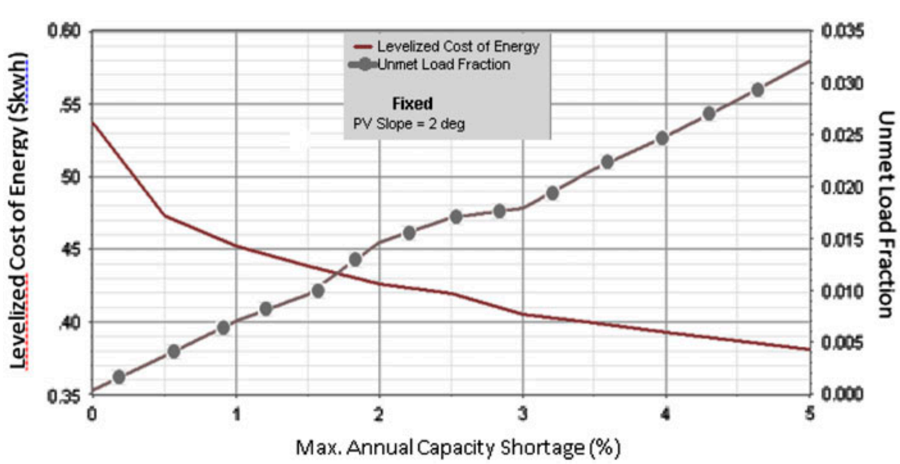

Fig. 13. Graph of levelized cost of energy and unmet load fraction against maximum annual capacity shortage at 2° PV slope.

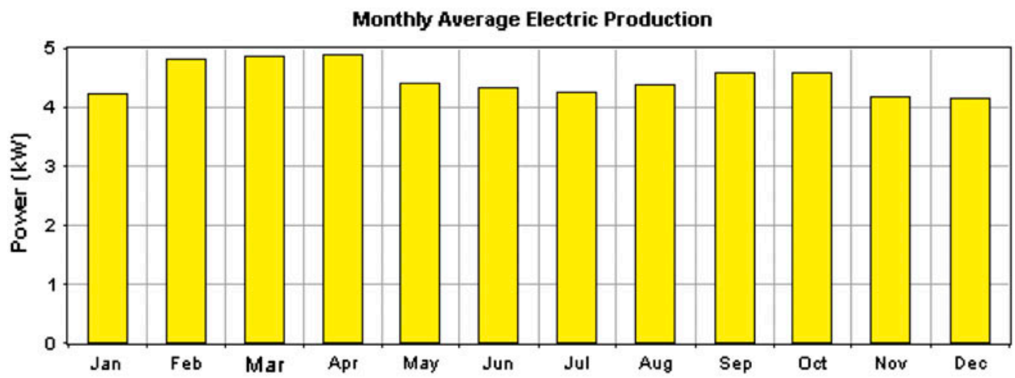

Fig. 14. Average monthly electric production.

Table 3
Power generated by PV modules

Quantity	Value
Rated capacity, kW	28
Mean output, kW	4.5
Mean output, kWh/d	107
Capacity factor, %	16
Total production, kWh/y	39,188

Table 4
Summary of excess electricity, unmet electricity, and capacity shortage

Quantity	kWh/y	%
Excess electricity	11,604	29.6
Unmet electric load	231	1.0
Capacity shortage	335	1.4

Table 5
Power transformation and losses by converter

Quantity	Inverter
Hours of operation, h/y	3,650
Energy in, kWh/y	26,510
Energy out, kWh/y	23,859
Losses, kWh/y	2,651

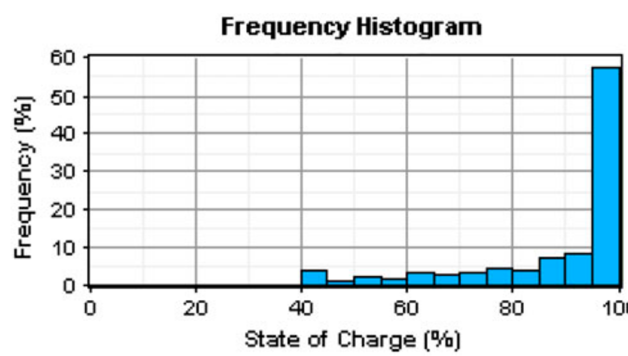

Fig. 15. Battery bank SOC.

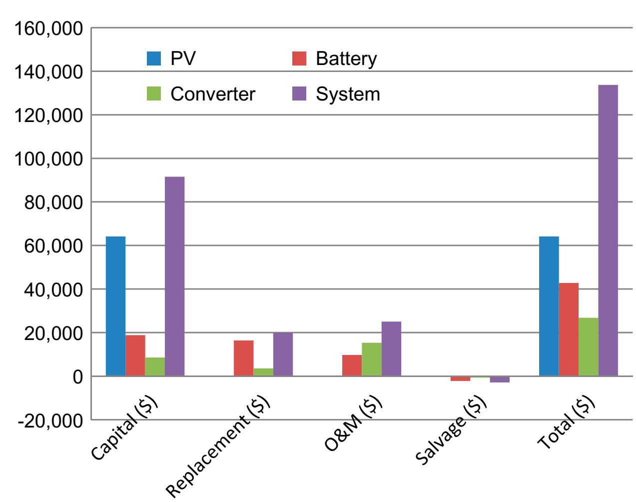

Fig. 16. Net present cost by component.

optimum size of the PV module used to build the system with 1.5% of unserved annual load is 28 kW, which enables production of 107 kWh/d and total production of 39,188 kWh/yr (Table 3). The PV system generates 29.6% of excess electricity, which is about 11,604 kWh/yr, leaving only about 231 kWh/yr of unmet electric load and capacity shortage of 335 kWh/yr (1.4%) (Table 4).

The optimum converter size is 12 kW. The converter, which operates 3,650 h/y, can convert 26,510 kWh/y, thereby producing 23,859 kWh/y with

Table 6
Stand-alone PV system cost

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	64,120	0	0	0	64,120
Battery	18,848	16,402	9,715	−2,196	42,769
Converter	8,568	3,575	15,340	−665	26,818
System	91,536	19,977	25,055	−2,861	133,707

losses of 2,651 kWh/y (Table 5). The state of charge (SOC) of the battery bank is in the range of 88–100% most of the time throughout the year (Fig. 15).

4.4. Cost of PV system

The initial cost to setup the optimum system is USD 133,707, with yearly operating and maintenance cost of USD 25,055. The total net present cost is USD 91,536 (Table 6). Fig. 16 shows the graphical view of the net present cost.

5. Cost of PV-BWRO system

The lifecycle cost and PV-BWRO system cost are represented by the total net present cost of the system. All incurred costs are calculated with future cash flows discounted to the present by using a discount rate. The cost includes initial cost of components, replacements, maintenance and operation, and miscellaneous costs. Revenue includes income from salvage value that occurs at the end of the project.

The cost includes

(1) purchase of the PV panels, batteries, inverter, charge regulator, and the RO system;
(2) installation of the system;
(3) maintenance of the components;
(4) replacement of the components throughout the life of the system; and
(5) operation and maintenance of the components throughout the life of the system.

All prices are assumed to escalate at the same rate over the lifetime of the project. With this assumption, inflation can be factored out of the analysis by using inflation-adjusted interest rates, rather than the nominal interest rate when discounting future cash flows to the present. The lifespan of the system is considered to be the life of the PV panels, which are the elements that have a longer lifespan. Calculation used for this project is similar to HOMER [8].

The total net present cost is calculated using the equation

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})}$$

where $C_{ann,tot}$ is the total annualized cost, i is the discounted rate, R_{proj} is the project's lifetime, and CRF is the capital recovery factor, given by the equation

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$

Table 7
Total cost of the PV-BWRO system

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	64,120	0	0	0	64,120
Vision 6FM200D	18,848	16,402	9,715	−2,196	42,769
Converter	8,568	3,575	15,340	−665	26,818
RO membrane elements	20,160	46,771	1,250	0	68,181
Pressure vessels	1,920	0	1,000	0	2,920
Pump	200	77	625	−67	836
Water storage tank	200	77	250	−67	461
Others	200	0	250	0	450
Total cost	114,216	66,903	28,430	−2,994	206,555

where i is the annual real interest rate, and N is the number of years.

The salvage value of each component at the end of the project's lifetime is calculated using the equation

$$S = C_{rep}\frac{R_{rem}}{R_{comp}}$$

where S is the salvage value, C_{rep} is the replacement cost of the component, R_{rem} is the remaining life of the component, and R_{comp} is the lifetime of the component. The total cost of the PV-BWRO system is USD 283,742 (Table 7), with the largest proportion attributed to PV panels (USD 107700).

6. Conclusion

Different design configurations are simulated using ROSA software. Simulations showed that two-stage RO system is the better option with lower energy consumption. Hybrid optimization model for electric renewables (HOMER) is used for techno-economic optimization of the PV power system. The minimum initial cost of the PV system is (102000$) and found at latitudes (50° S/N), while the maximum initial cost is (133000$) and found at latitude (−60°). The economic performance of the PV system is then optimized under Malaysia latitude by allowing portions of the annual load to go unserved. The result shows that the optimum combination is a system with a 28 kW PV array, 76 batteries, and 12 kW converter with 1.5% annual unmet load fraction at 2° of PV slope. Allowing a small percentage of loads to go unserved throughout the year reduces the cost of the system. Powering RO system with PV power showed different initial cost for different latitudes.

References

[1] S. Abdallah, M. Abu-Hilal, M.S. Mohsen, Performance of a photovoltaic powered reverse osmosis system under local climatic conditions, Desalination 183 (2005) 95–104.
[2] J.H. Lindemann, Wind and solar powered seawater desalination, Desalination 168 (2004) 73–80.
[3] D. Herold, A. Neskakis, A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria, Desalination 137 (2001) 285–292.
[4] E. Tzen, K. Perrakis, P. Baltas, Design of a stand-alone PV-desalination system for rural areas, Desalination 119 (1998) 327–334.
[5] S. El-Manharawy, A. Hafez, Water type and guidelines for RO system design, Desalination 139 (2001) 97–113.
[6] ROSA. http://www.dowwaterandprocess.com/support_training/design_tools/rosa.htm. Accessed February 2013.
[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] HOMER: The Micro-Power Optimization Model. Software produced by NREL. https://analysis.nrel.gov/homer/. Accessed February 2013.
[9] M.A. Alghoul, P. Poovanaesvaran, K. Sopian, M.Y. Sulaiman, Review of brackish water reverse osmosis (BWRO) system designs, Renewable Sustain. Energy Rev. 13 (2009) 2661–2667.
[10] F. Vince, F. Marechal, E. Aoustin, P. Breant, Multi-objective optimization of RO desalination plants, Desalination 222 (2008) 96–118.
[11] M.S. Mohsen, J.O. Jaber, A photovoltaic-powered system for water desalination, Desalination 138 (2001) 129–136.
[12] W. Gocht, A. Sommerfeld, R. Rautenbach, T.H. 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.
[13] S.A. Alajlan, M.S. Smiai, Performance and development of PV—plant for water pumping and desalination for remote area in Saudi Arabia, Renewable Energy 8 (1996) 441–446.
[14] M.S. Mohsen, J.O. Jaber, A photovoltaic powered system for water desalination, Desalination 138 (2001) 129–136.
[15] Introduction and summary of the International Workshop on Desalination Technologies for Small and Medium Size Plants with Limited Environmental Impact, Desalination 122 (1999) 115–121.
[16] A. Zhu, P.D. Christofides, Y. Cohen, Energy consumption optimization of reverse osmosis membrane water desalination subject to feed salinity fluctuation, Ind. Eng. Chem. Res. 48 (2009) 9581–9589.
[17] A. Zhu, P.D. Christofides, Y. Cohen, On RO membrane and energy costs and associated incentives for future enhancements of membrane permeability, J. Membr. Sci. 1 (2009) 344.
[18] A. Zhu, A. Rahardianto, P.D. Christofides, Y. Cohen, Reverse osmosis desalination with high permeability membranes – cost optimization and research needs, Desalin. Water Treat. 15 (2010) 256.
[19] A. Bartman, A. Zhu, P.D. Christofides, Y. Cohen, Minimizing energy consumption in reverse osmosis membrane desalination using optimization-based control, J. Process Control 20 (2010) 1261.
[20] A. Zhu, P.D. Christofides, Y. Cohen, Effect of stream mixing on RO energy cost minimization, Desalination 261 (2010) 232–239.
[21] P. Poovanaesvaran, M.A. Alghoul, k. Sopian, N. Amin, M.I. Fadhel, M. Yahya, Design aspects of small-scale photovoltaic brackish water reverse osmosis (PV-BWRO) system, Desalin. Water Treat. 27 (2011) 210–223.
[22] A. Zhu, P.D. Christofides, Y. Cohen, Minimization of energy consumption for a two-pass membrane desalination: Effect of energy recovery, membrane rejection and retentate recycling, J. Membr. Sci. 126 (2009) 339.
[23] G. Al-Enezi, N. Fawzi, Design consideration of RO units: Case studies, Desalination 153 (2002) 218–286.
[24] A. Zhu, P.D. Christofides, Y. Cohen, Effect of thermodynamic restriction on energy cost optimization of RO membrane water desalination, Ind. Eng. Chem. Res. 48 (2009) 2010.
[25] NASA Surface Meteorology and Solar Energy. http://eosweb.larc.nasa.gov/sse/. Accessed February 2013.
[26] Solarbuzz LLC. http://www.solarbuzz.com. Accessed February 2013.
[27] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems—A technical and economical experimental comparative study, Desalination 221 (2008) 17–22.