Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28200

263 (2022) 25–31
July

Performance and cost analyses of hybrid diesel-photovoltaic powered small brackish water reverse osmosis system in Saudi Arabia

Abdulmajeed Khalid Al-Rubayan[a], Ridha Ben Mansour[b,*], Fahad A. Al-Sulaimana[a,b]

[a]*Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, 31261*
[b]*Interdisciplinary Research Center for Renewable Energy and Power Systems, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, 31261, email: ridha.benmansour@kfupm.edu.sa (R.B. Mansour)*

Received 28 February 2022; Accepted 12 April 2022

ABSTRACT

The need for water is certainly very alarming in the Middle East and North Africa (MENA) region where water demand for domestic, agriculture, and industrial applications continue to increase, and on the other hand, water resources are increasingly becoming scarce (low precipitation and depletion of renewable groundwater). Inland desalination process in off-grid or remote areas contributes a significant portion to the water supply in Saudi Arabia. However, inland desalination systems have many challenges to be well implemented such as limited water distribution, water transmission cost from seawater desalination plants to the inland area. Many wells in Saudi Arabia have relatively high salinity water, which is not directly usable. This study aims to find the best hybrid diesel-photovoltaic powered reverse osmosis (RO) system to desalinate brackish water that has 6,000 ppm salinity for a remote area near Ummluj City in the Kingdom. Each RO system produces 202 m^3/d for two purposes: drinking and household purposes. A batch mode that operates 5 h/d is studied. The hybrid system composed of conventional and renewable energy systems driven brackish RO system are modelled using ROSA and HOMER software. Besides, the advantages of adding a pressure exchanger (PX) and a second-stage are investigated. Further, the effect of the fuel price on the cost of water production is analysed. It was found that adding a second storage tank for household applications with 1,000 ppm reduces the levelized cost of water by 11%. Furthermore, using a pressure exchanger leads to 26% reduction in the specific energy consumption (SEC) while adding a second-stage reduces the SEC by 22%. However, adding PX is economically feasible for fuel price higher than 40 USD/L.

Keywords: Solar energy; Fresh water; Optimization; Desalination; Batch mode; Remote areas

1. Introduction

The demand growth is more pronounced and rising in GCC, especially in KSA, with the desalination capacity share of 22% worldwide and 54% in GCC by the year 2017. In the year 2017, KSA has a total installed capacity of 8.3 million m^3/d with 48 operational plants and is expected to increase by up to 10.8 million m^3/d by 2030. Moreover, Saudi Arabia has an abundant solar resource with an average annual solar radiation of about 2,200 kWh/m^2. The global horizontal irradiance (GHI) varies throughout the Arabian Peninsula ranging between 3.7–7.9 and 4.1–7.5 kWh/m^2/d for the east and west coasts, respectively, while the central part receives 4.0–7.7 kWh/m^2/d KSA [1]. As a result, the kingdom of Saudi Arabia is set to target towards deployment of RE in general and solar photovoltaic (PV), in particular, to reach a planned capacity of 20 GW by 2023 and a long term plan to reach 40 GW by 2030 as stated by Renewable Energy Project Development Office. Further, the KSA government is looking for the

* Corresponding author.

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

enhancement of efficiency and reducing the consumption of energy. Thus, the kingdom has to explore and develop sustainable production and supply of high quality freshwater by combining solar energy resources with the latest desalination technologies.

Inland desalination process in off-grid or remote areas contributes a significant portion to the water supply in Saudi Arabia. However, inland desalination systems have many challenges to be well implemented, such as limited water distribution water transmission cost from seawater desalination plants to the inland area. Inland desalination capacity in Saudi Arabia is over 3.600 million m^3/d, with more than 750 brackish water reverse osmosis plants (BWRO) in operation. Most of these plants use a diesel generator to meet the power requirement. Additional cost associated with fuel transportation increases the water production cost and energy consumption. As Saudi Arabia tries to reduce diesel consumption, deployment of renewable energy sources compatible with the desalination technologies is needed.

Several small and medium-scale renewable energy powered desalination plants have been installed worldwide. The reverse osmosis (RO) membrane desalination driven by solar PV energy is the most suitable combination of renewable energy and desalination as concluded by Karimi et al. [7]. Indeed 62% of global renewable energy installed capacity was used to power the reverse osmosis system in 2015 [2].

Alawaji et al. [3] built a PV-RO plant for a remote area in Saudi Arabia to desalinate brackish water for drinking purposes. The plant production was 15 m^3/d, where the PV size was 10 kW with a battery. Further work was conducted in 1996 by making two options: battery and battery-less [4]. They state that the performance of the plant was excellent, and the system was reliable. PV modules cost 42% of the total investment, while 31% for batteries and charge controllers. Another PV-RO setup evaluation was installed in Brazil in 2009. Riffel and Carvalho [5] compared two scenarios. In the first scenario, 2 PV modules were used to operate the RO pump and the module for the well pump. In the second scenario, all 3 modules are used for both loads. The study shows that the second scenario was the best. Elasaad et al. [6] evaluated a PV-RO setup in a remote area in Mexico, which was operating for 6 y. The setup desalinates well water with a 1 m^3/d production rate and 800 W power generation. The study shows that 1 m^3 of desalinated water costs USD9. Half of the capital cost was for the RO system, pre-treatment, and post-treatment, while 25% was for the PV modules and electronics. Regarding the operation expenditure (OPEX), 61.5% was for operation cost, and 9.23% for RO maintenance cost. The system is efficient and reliable. Recently, a comparative study between electrodialysis reversal (EDR) and RO systems integrated with PV modules was performed by Karimi et al. [7]. They concluded that for low salinity water, PV-EDR is more cost-efficient than PV-RO, while for high salinity water is the opposite.

2. Feasibility studies

PV-RO is technically effective solution to water shortage for off-grid or remote areas. However, the cost for water production via PV-RO is characterized by high volatility and vary substantially by location, water types, system demand, and plant size [8]. The water cost for typical reverse osmosis powered by PV reported in recent literature varies from 1.65 to 15.6 USD/m^3 [9,10]. A cost analysis of small PV powered brackish water reverse-osmosis with a battery system for Egypt desert conditions was conducted [11]. Even feed water characterised by low salinity (<2,000 ppm), the estimated cost of producing 1 m^3 of clean water is 3.73 USD.

Helal et al. [12] conducted a cost analysis of off-grid PV connected SWRO in the UAE. Three alternative power source cases are considered in this study: diesel generator, hybrid diesel-PV, and PV panels. The fresh water capacity for all the studied systems was 203/d. Simulated results showed that the specific water cost and specific energy consumption are USD7.64 and 7.74 kWh for the fully-diesel case, USD7.21 and 7.73 kWh for the hybrid case, and USD7.34 and 7.33 kWh for the fully-PV case.

Bilton and Kelley [13] developed a techno- economic approach based on optimization techniques to achieve the optimum lifetime cost of water production with respect to required water demand. The optimization variables considered in this study are the types of the power source (diesel generators, solar PV, wind and their combinations), design of RO, and water storage size. The developed methodology was used to design a RO system with a capacity of 10 m^3/d for three different locations (Honduras, Eritrea, and Australia). They concluded the cost-effective configuration to supply water is a function of wind speed, solar radiation, and fuel price. Other studies confirm the critical role of location in determining the feasibility of PV-RO system [9,12,13].

Based on the above literature, the water desalination through PV-RO is technically feasible. However, the cost of water production and power consumption are still relatively high, and vary substantially by location, water types, system demand, plant size, and local water transport cost [8,10]. A limited number of studies focusing on feasibility of PV-RO in the Saudi rural areas that suffer from clean water scarcity and high water cost, while Saudi Arabia has an abundant solar resource and large amounts of brackish waters.

The main objective of this study is to analyse the performance and cost of a hybrid diesel-PV powered RO system to desalinate brackish well water for a remote area in Saudi Arabia.

3. Mathematical model

3.1. Reverse osmosis modelling

A schematic of a reverse osmosis system in batch mode is depicted in Fig. 1. A second storage tank for household purposes with a salinity of 1,000 ppm. Excess cleaned water for drinking use is blended with the pre-treated water to reduce the total salinity to meet the required salinity for household applications. In addition, the studied system is included a pressure recovery (PX) converting the mechanical (in form of pressure) from high-pressure brine flow to low-pressure feed flow.

A simple model was developed to predict the flow, the pressure and the salinity of fresh water out of the membrane. The main equations for the RO process simulation and

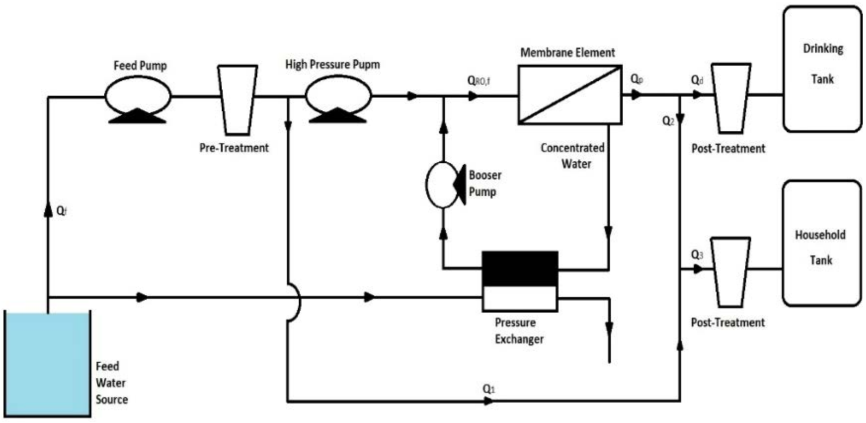

Fig. 1. Schematic diagram RO system with second storage tanks and PX.

design can be found in [8,14]. The developed model assisted reverse osmosis system analysis (ROSA) software is used to determine design parameters of the RO system (desalination, capacity, membrane pressure, and power required).

3.2. Energy source modelling with HOMER

The energy requirements for the RO system were determined based on water salinity and water depth. The energy sources considered in this study are provided by three sources: photovoltaic Panels, batteries, and diesel generator. For the PV-RO, it is assumed that the system will operate when solar energy is available. The average permeate flow rate during operation is calculated by dividing the daily RO production capacity in m^3/d by the number of daylight hours.

The rated power equation for photovoltaic panels is given by [15]:

$$P_{\text{PV-rated}} = \eta_{\text{PV}} A_{\text{PV}} G_{\text{STC}} \tag{1}$$

where $P_{\text{PV-rated}}$ is the rated power generated by the solar panel in W, A_{PV} is the panel area, η_{PV} is the panel efficiency and G_{STC} is the incident solar energy at the standard test condition. The solar module efficiency is affected by the ambient temperature. The actual PV power output from the solar PV operating under real weather conditions can be estimated using the following equation.

$$P_{\text{PV-output}} = P_{\text{PV-rated}} F_{\text{PV}} \left(\frac{G}{G_{\text{STC}}}\right) \left[1 + \alpha_p \left(T_{\text{cell}} - T_{\text{cell-STC}}\right)\right] \tag{2}$$

where $P_{\text{PV-output}}$ is the real power generated by the solar panel, G is the incident solar energy on the panel F_{PV} is the derating factor which account for the loss due to wiring, shading, snow and α_p is the cell temperature coefficient. T_{cell} and $T_{\text{cell-STC}}$ are the cell temperatures at real condition and standard test conditions, respectively.

To model the power system composed of PV, diesel generator and batteries, Hybrid Optimization Model for Electric Renewable software (HOMER) is used in this study. It is a tool for designing, analysing, and optimizing hybrid energy system configurations based on their technical and economic merits. For each simulated configuration, HOMER calculates its life-cycle cost including the capital, operating and maintenance costs and fuel and interest rate [15]. The schematic diagram of the hybrid system considered in this study is shown in Fig. 2.

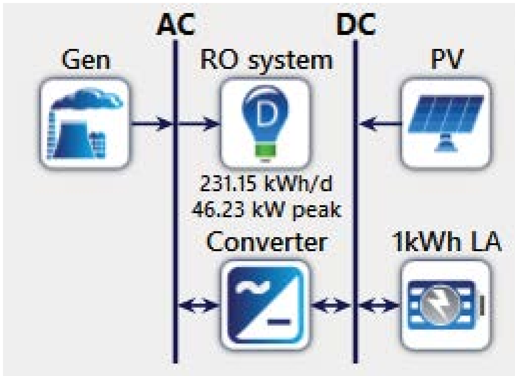

Fig. 2. Schematic diagram of the hybrid system.

3.3. Economic analysis

For an economic analysis of hybrid diesel-PV powered brackish water RO system, an excel program based on the annualized life-cycle method was developed to calculate the capital expenditure (CAPEX), operational and maintenance expenditure (OPEX) of all the components of the hybrid system. The levelized cost of water (LCOW), the levelized cost of energy (LCOE), the payback period was estimated by varying the price of fossil fuel. The total equivalent annul cost is the summation of the total equivalent annual cost of the power source (PV and diesel generator) and RO system. A detailed explication of the economic approach can be found in [8].

The LCOW is calculated using the following equation:

$$\text{LCOW} = \frac{\sum \text{CAPEX} \times \text{CRF} + \text{OPEX}}{365\tau \times Q_{\text{cap}}} \tag{3}$$

CAPEX is the total capital costs of all components of reverse osmosis system and the power system. CAPEX is converted into equivalent annual costs using the capital recovery factor (CRF) given by is given by:

$$\text{CRF} = \frac{z(1+z)^n}{(1+z)^n - 1} \tag{4}$$

where z is discount rate and n the amortization period.

The LCOE is the total annualised cost of the power system divided by the yearly electrical load served.

3.4. Input data and methodology

For predicting performance and cost analysis for hybrid diesel-PV powered well RO system; we used ROSA and HOMER simulations. The first step involves obtaining environment resources, water quality and capacity, and hybrid system configuration. Design parameters of RO system is then calculated using (ROSA). The second step consists in modelling and simulating ad optimizing the power energy system. Finally, economic analysis of the whole system is performed using the excel sheet program. The input data for of hybrid diesel-PV powered RO system used in this study are listed in Table 1.

4. Result and discussion

4.1. One stage RO simulation

Detailed economics related to the batch mode configuration of the optimized diesel-PV-RO were simulated using input data listed in Table 1. Table 2 shows the system configuration for different renewable energy fraction used to generate annual electricity and estimate annual CO_2 savings. With almost 51.6% renewable energy fraction, the system is estimated to generate annual energy of 81,869 kWh and save almost 31,591 kg of CO_2 annually. The LCOE and LCOW for various combinations of renewable energy fraction range between 0.12 to 0.18 USD/kWh and 0.8 to 0.9 USD/m^3, respectively as shown in Table 3. The optimal configuration was obtained using a diesel generator only, because of the low price of fossil fuel of 0.13 USD/L. With increasing renewable energy penetration, the costs associated with renewable energy components also increase resulting in a substantial rise in total equivalent annual cost for the hybrid system. For the value of RE penetration higher than 30%, the cost function decreases. The second optimal configuration after the diesel-only configuration is another combination of PV with 90.8% (99.3 kW) penetration with a 47 kW generator and 1 kWh battery connected to a 46.9 kW converter. This is because, at high renewable energy fraction, the number of

Table 1
Main input parameters for diesel-PV-RO analysis

Component	Parameters	Value
RO system	Recovery ratio (one-stage)	50%
	Capital cost of RO system	163,000 USD
	Capital cost of PX	72,000 USD
	O&M of RO	10,500USD
	HPP replacement (15 y)	23,700 USD
	Pump efficiency [8]	80%
	ERD efficiency (PX) [16]	96.7%
	Pre-treatment and post treatment power required	15% HPP power
Flat plate PV	PV cost for capacity <1 kW	2,500 USD/kW
	PV cost for capacity <10 kW	2,000 USD/kW
	PV cost for capacity <100 kW	1,500 USD/kW
	Efficiency [17]	17%
	Temperature coefficient [17]	–0.45%/oC
Lead acid battery	Nominal capacity [17]	1 kWh
	Capital cost [17]	300 USD
	Life time [17]	5 y
	Discount rate	5%
Diesel generator	Lower heating value [17]	43.2 MJ/kg
	Carbon content (%) [17]	88%
	Capital cost [17]	500 USD/kW
	Life time [17]	15,000 USD
	O&M [17]	0.03 USD/h
	Initial fuel price	0.13 USD
	Fuel transportation	325 USD/y

Table 2
Overall optimization results

Renewable fraction (%)	PV (kW)	Gen (kW)	Battery (kWh)	Converter (kW)	Excess electricity (kWh/y)	Percentage of excess electricity	CO_2 emission (kg/y)	CO_2 saving (kg/y)
100%	141	0	0	49	146,893	62%	–	63,380
91%	99.3	47	1	46.9	85,816	50%	6,012	57,368
81%	91.6	47	1	46.9	81,484	48%	12,472	50,908
73%	87	47	4	46.6	81,267	48%	17,927	45,453
63%	80.9	47	17	47.9	79,778	48%	24,290	39,090
52%	76.3	47	5	51.6	81,869	49%	31,789	31,591
43%	72	47	13	48	82,473	49%	37,491	25,889
33%	66.9	47	17	48.8	83,026	49%	44,293	19,087
22%	54	47	21	49.6	71,240	46%	51,574	11,806
13%	38	47	1	19.8	51,759	38%	51,221	12,159
0%	0	47	0	0	0	0%	63,380	0

Table 3
Detailed cost results for batch mode option 2 with ERD

PV penetration	An_{total} (USD)	LCOW (USD/m^3)	LCOE (USD/kWh)	Energy cost percentage	RO cost percentage
100%	44,159	0.90	0.18	65%	35%
91%	42,164	0.86	0.16	68%	32%
81%	42,195	0.86	0.16	68%	32%
73%	42,980	0.87	0.17	67%	33%
63%	44,306	0.90	0.19	65%	35%
52%	44,132	0.90	0.18	65%	35%
43%	45,445	0.92	0.2	63%	37%
33%	46,326	0.94	0.21	62%	38%
22%	46,450	0.94	0.21	62%	38%
13%	43,807	0.89	0.18	65%	35%
0%	39,193	0.80	0.12	73%	27%

batteries has been reduced; only one battery is considered for RE fraction higher than 81%.

Fig. 3 shows the LCOW variation with renewable energy penetration. The LCOW is slightly higher when using renewable energy power to drive the RO system due to the high cost associated with the renewable. As the power cost has a high share contribution to the total cost of water production, LCOW and LCOE have the same variation with renewable energy fraction. The same optimal configuration containing a 47 kW generator and 1 kWh battery connected to a 46.9 kW converter is obtained for LCOW and LCOE.

4.2. Effect of number of stage and ERD

Fig. 4 depicts the variation of LCOW with RE power penetration for one and two-stage RO system with and without ERD system. Adding a stage would indeed increase the recovery ratio of the RO system and reduce the LCOW of the hybrid diesel-PV powered RO. The two-stage RO configuration includes two trains of pressure vessels allowing for maximum recovery of permeate which positively affects the energy consumed. The recovery ratio is increased from 50% to 65% for one-stage and two-stage RO systems, respectively, leading to 22% reduction in the specific energy consumption. As a result, the two-stage RO system has the lowest total cost of water compared with one stage configuration. Besides, using a pressure exchanger as an energy recovery device in this mode is not cost-effective due to the initial high investment of the energy recovery system (PX).

4.3. Effect of fuel price

Sensitivity analysis is performed to study the effect of fuel prices on the cost of water production as shown in Fig. 5. It is clear that the fuel price has a great impact on the cost of water production. LCOW linearly increases with the increase of the fuel price. Besides, for the three studied configurations (Batch, batch with PX and batch with two stages), the lowest LCOW was found at low fuel price. Fig. 5 shows that the use of PX as ERD becomes economically feasible when the diesel price increases to USD 0.4/L which can be considered as the breakeven point between batch and batch with PX configuration. As the fuel price increases, its cost-sharing in the total cost of water production increases also until reaching the breakeven point at USD 40/L. it is concluded that the two-stage RO system

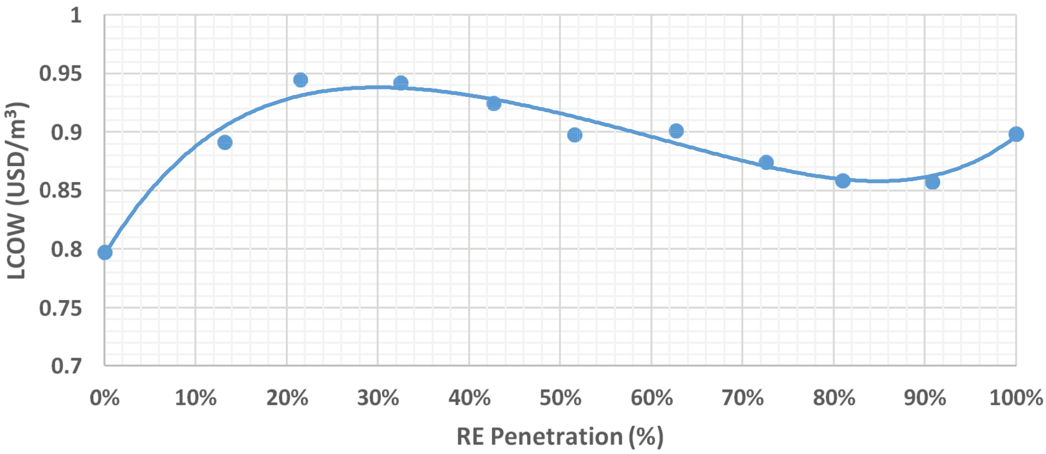

Fig. 3. Levelized cost of water variation with RE penetration.

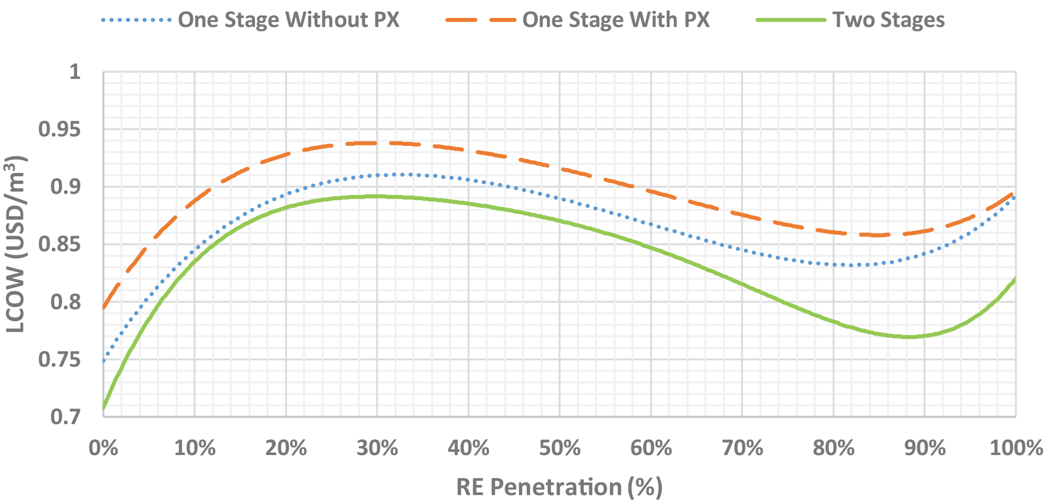

Fig. 4. LCOW vs. RE penetration for batch mode cases.

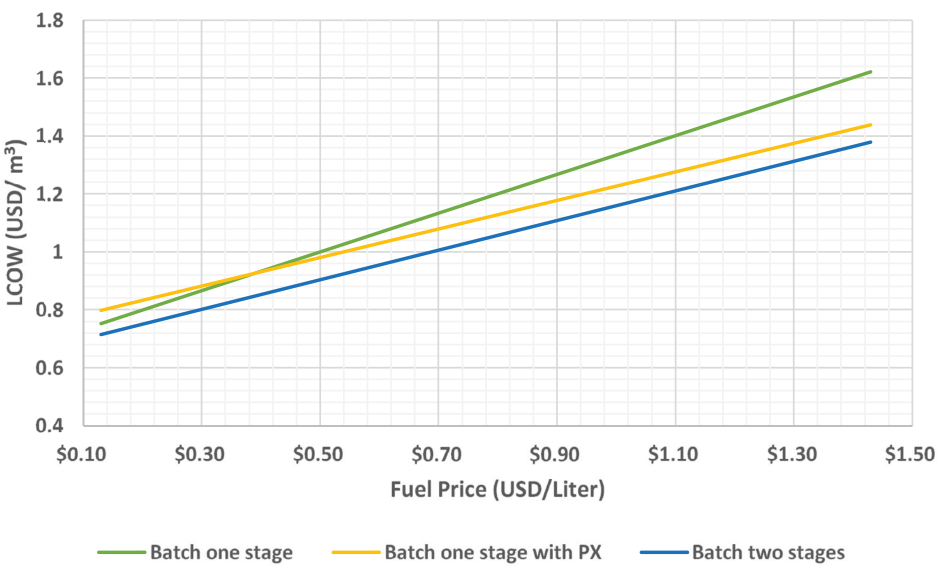

Fig. 5. LCOW for different fuel price at diesel powered RO system.

has the lowest total cost of water independent of fuel price variation.

5. Conclusion

Performance and cost analyses of hybrid diesel-PV powered brackish water RO system for supplying fresh water to a small rural community in KSA was studied. It was found that the power cost has a high share contribution to the total cost of water production with about 65%. The simulated results showed that LCOE and LCOW for different combinations of renewable energy system with RO system range between 0.12–0.18 USD/kWh and 0.8–0.9 USD/m^3. Further, it is concluded that the two-stage RO configuration positively affects the recovery ration leading to leading to 22% reduction in the specific energy consumption compared with one-stage system. For the integration of pressure exchanger (PX), it is demonstrated that it is cost effective solution for the diesel prices higher than 40 USD/L. At lower fuel prices (<40 USD/L), it is not cost-effective due to the high initial investment of the pressure exchanger.

The obtained results will be very valuable to identify the cost effective and technical efficient systems for best hybrid diesel-PV powered reverse osmosis (RO) systems for different rural areas in KSA. Thus, this proposed study would lead to the acceleration of Solar PV distribution in the inland desalination market and the reduction of fossil fuel use in KSA as well as ensure sustainable use of water resources.

Acknowledgements

The authors would like to acknowledge the resources provided by the Interdisciplinary Research Center for Renewable Energy and Power Systems at King Fahd University of Petroleum & Minerals.

References

[1] A. Hepbasli, Z. Alsuhaibani, A key review on present status and future directions of solar energy studies and applications in Saudi Arabia, Renewable Sustainable Energy Rev., 15 (2011) 5021–5050.
[2] N. Ghaffour, J. Bundschuh, H. Mahmoudi, M.F.A. Goosen, Renewable energy-driven desalination technologies: a comprehensive review on challenges and potential applications of integrated systems, Desalination, 356 (2015) 94–114.
[3] S. Alawaji, M.S. Smiai, S. Rafique, B. Stafford, PV-powered water pumping and desalination plant for remote areas in Saudi Arabia, Appl. Energy, 52 (1995) 283–289.
[4] 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.
[5] D.B. Riffel, P.C.M. Carvalho, Small-scale photovoltaic-powered reverse osmosis plant without batteries: design and simulation, Desalination, 247 (2009) 378–389.
[6] H. Elasaad, A. Bilton, L. Kelley, O. Duayhe, S. Dubowsky, Field evaluation of a community scale solar powered water purification technology: a case study of a remote Mexican community application, Desalination, 375 (2015) 71–80.
[7] L. Karimi, L. Abkar, M. Aghajani, A. Ghassemi, Technical feasibility comparison of off-grid PV-EDR and PV-RO desalination systems via their energy consumption, Sep. Purif. Technol., 151 (2015) 82–94.
[8] A.M. Bilton, R. Wiesman, A.F.M. Arif, S.M. Zubair, S. Dubowsky, On the feasibility of community-scale photovoltaic-powered reverse osmosis desalination systems for remote locations, Renewable Energy, 36 (2011) 3246–3256.
[9] A.M. Bilton, S. Dubowsky, The modular design of photovoltaic reverse osmosis systems: making technology accessible to nonexperts, Desal. Water Treat., 51 (2013) 702–712.
[10] M.W. Shahzad, M. Burhan, L. Ang, KC. Ng, Energy-water-environment nexus underpinning future desalination sustainability, Desalination, 413 (2017) 52–64.
[11] 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.
[12] A.M. Helal, S.A. Al-Malek, E.S. Al-Katheeri, Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates, Desalination, 221 (2008) 1–16.
[13] A.M. Bilton, L.C. Kelley, Design of power systems for reverse osmosis desalination in remote communities, Desal. Water Treat., 55 (2015) 2868–2883.
[14] Dow, FILMTEC™ Reverse Osmosis Membranes, Technical Manual, Dow Water & Process Solutions, n.d.
[15] HOMER Pro - Microgrid Software for Designing Optimized Hybrid Microgrids n.d. Available at: https://www.homerenergy.com/products/pro/index.html (Accessed December 29, 2020).
[16] "DESALINATION, Products Catalog," Energy Recovery Company, 2018.
[17] HOMER – Hybrid Renewable and Distributed Generation System Design Software n.d. Available at: https://www.homerenergy.com/index.html (Accessed December 29, 2020).