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Distributed generation of freshwater through reverse osmosis desalination units by using various energy sources, techno-economic feasibility study

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ABSTRACT

Nowadays, Iran, the same as many other countries, is suffering from freshwater shortage. Hence, the desalination of seawater in the coastal regions and desalination of brackish water in the central, eastern, and western parts of Iran can be promising solutions. For this aim, the use of seawater reverse osmosis and brackish water reverse osmosis (BWRO) units is proposed. In this article, four different methods to supply the required power have been assessed. They are compared in five cities of Iran to determine the most economical mode of freshwater production in different regions. The grid, gas engines, diesel engines, and photovoltaic solar panels are used to provide power. The results show that the increment in inlet water total dissolved solids causes the required pressure and specific energy consumption to increase. Also, the BWRO system powered by a gas engine seems to be the most economical system with levelized cost of water in the range of 0.89–0.92 US$/m^3. Moreover, the minimum required solar energy generation to make the considered RO unit economical is determined. Allocating the emission penalty cost of the fossil-fuel-powered unit to the solar PV system as the environmental subsidy can decrease the period of return by 26.9%.

Keywords: Medium scale reverse osmosis desalination unit; Feasibility study; Solar PV system; Sensitive analysis; Economic analysis; Scenario analysis

1. Introduction

1.1. Medium-scale desalination units' importance

Water scarcity in the Middle East and North Africa is sharply increasing, and supplying quality freshwater has become a clear issue. Iran, located in middle east region, has faced water crisis in recent years, and its small and large cities are exposed to water stress. Reduction of rainfall and misuse of the available water resources, especially in the agricultural sector, has led the country to face major challenges. It is indicated that the magnitude of rainfall in 2017 decreased by about 25.8% in comparison with 2016 [1,2].

The total online capacity of desalination plant in June 2017 is 92.5 million m^3/d and the contracted capacity of desalination plant on this date (June 2017) is 7.3 million m^3/d and the contribution of Iran in this registered capacity is under 1% [3]. According to the International Desalination Association (IDA) report in 2018, the 65% of total desalination plant systems have a small and medium scale, and the new trend of the market shows that the more than 90% of new developed desalination plant are constructed based on the reverse osmosis's technology [3,4].

The reverse osmosis plants are capable to remove 99% of total dissolved solids (TDS) of feed water and make a high-quality water. Also, in contrast to the other desalination

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methods, the RO units have more reasonable price and they are more compact. The RO units need less space than other desalination methods and this property makes the special for the small and medium scale desalination market. Because of access to seawater in the north and south of Iran and the available low-quality surface water resources in central, eastern, and western parts, the usage of medium-scale desalination as a medium-term solution for supplying healthy drinking water is suggested [5,6]. According to the presented information, the medium-scale desalination plant based on reverse osmosis (RO) technology is considered in this study.

1.2. Electrical energy sources for RO desalination

Because of the importance of desalination systems, some incentives are offered in many countries. One of them is the lower electricity price for reverse osmosis units. However, the problem is that desalination systems have to be installed in a place where has to access to the grid. Also, it should be assessed whether allocating such budget as a subsidy is the most economical way or not. It is estimated that electricity, in Iran, costs about 10 US cent. Also, the network energy loss is another demerit of using the grid as the energy source for RO systems. Therefore, investigation of using the other energy sources are recommended for desalination unit energy supply. Hence, in this study, utilizing a gas engine, a diesel engine, and a photovoltaic solar system is subjected beside the grid (without government subsidy), and they are compared from the technical and economic angle.

The considered subject of this article has been evaluated in many studies over the past years, which will be discussed in this part. Earth seems to have enough power to cover the demand for electrical power in the world but not by a single source; for this reason, recent research has been conducted to design the configuration of the system in an optimal way [7,8].

Ahmad and Schmid [9] studied the feasibility of brackish water desalination in the Egyptian deserts and rural regions using PV systems. They illustrated that the cost of producing 1 m^3 of freshwater is 3.73 US$. This cost is evaluated for the small size of the system and if the system size is increased, the cost of generating fresh water will be decreased.

Bouguecha et al. [10] investigated the case studies on the small-scale desalination pilots powered by renewable energy in Tunisia. Their experimental results show that the system is technically feasible, but it needs more optimization on the operational parameter to be economically feasible as well.

Alsheghri et al. [11] studied the technical and economic aspects of a solar photovoltaic that powered a RO Plant at Masdar Institute. The output results illustrated that the period of return for such a system is about 23.3 y, and was not economically feasible. They also mentioned that the system could decrease Green House Gas production by using the generated energy from the PV system.

Other studies were subjected to the topic of reverse osmosis system that is powered by renewable energy in 2015 [12,13]. Caldera et al. [14] demonstrated how reverse osmosis (SWRO) plants in seawater can be powered solely by renewable energy, which is necessary to meet the increasing global demand for water. The results show that for demanding regions in 2030, the levelized cost of water (LCOW), which includes water production, electricity, water transportation, and water storage costs, is found to be in the range of € 0.59/m^3 to € 2.81/m^3. Maleki et al. [15] and Zhang et al. [16] have used a reverse osmosis system to meet the need for freshwater in the eastern regions of Iran. Its required power is supplied by wind or solar energy. An algorithm has been proposed to predict the weather. The results show that the best way to supply drinking water is to use photovoltaic panels and batteries. Wu et al. [17] in 2018 supplied drinking water to areas in Iran using a reverse osmosis unit. The power consumption of this unit is provided by solar energy and a diesel engine. The results show that using PV panels with diesel and battery engines to provide power is more economical and environmentally friendly than using each of solar panel or diesel engine alone. da Silva et al. [18], in 2018, studied the cost analysis of using the different energy sources in RO desalination plant in Brazil. Results illustrated that the most cost-effective method for RO unit electrical energy production is natural gas, and the produced water using this method has a cost of 0.88–1.97 US$/$m^3$. Mostafaeipour et al. [19] studied the off-grid photovoltaic systems usage for a reverse osmosis desalination system. Their study showed that the cost of generated water is about 1.96–3.02 US$/$m^3$.

In conclusion, desalination driven by renewable energy has proved to be a sustainable, economical, and environmentally friendly solution for water deficiency issues in remote areas. Karavas et al. [20] show that implementing an energy management program to combine RO device with PV solar panel and battery bank demonstrates lowest cost and lowest power losses.

In this paper following analyses are conducted:

- A comprehensive technical and economic feasibility analyses is carried out on the usage of RO desalination unit throughout the country (case study of Iran) to generate the required drinking water.
- This study includes both types of input raw water (the brackish water with maximum total dissolved solid of 5,000 ppm and the seawater with maximum total dissolved solid of 45,000 ppm) in different regions of the country (Iran) with special access to raw water input.
- Also, various sources of energy (such as grid electricity, natural gas through gas engines, diesel fuel through diesel engines, and solar PV energy) have been investigated as the source of energy for RO desalination units.
- The annualized cost of system (ACS) method has been used which shows the impact of actual energy prices and the impact of government subsidy policies on the prime cost of produced freshwater.
- Finally, the required policy packages in order to support the distributed freshwater production units is developed. Also, the environmental analysis of the proposed scenarios has been evaluated in order to determine the amount of emission penalty cost and its impact on the economic feasibility of the system.

2. Different scenarios description

Four scenarios are considered in this study. In these scenarios, the required energy is supplied by certain energy sources. Also, two types of RO desalination system are considered (brackish water RO and seawater RO). The capacity of desalination unit is 100 $/m^3. Fig. 1 shows the constructed brackish water RO unit, which is developed as a pilot for this study. Also, Fig. 2 shows the different energy suppliers for the considered scenarios.

The capacity of desalination unit is 100,000 L/d, and this capacity is sufficient to supply the drinking water for 20,000 people/d (the average of drinking water consumption per capita is 2–5 L/d. As mentioned before, these units are designed in two inlet water salinity, brackish water reverse osmosis (BWRO) (inlet water salinity 2,000–5,000 ppm; this package is placed inside a 20 ft container) and the seawater reverse osmosis (SWRO; inlet water salinity 18,000–50,000 ppm; this package is placed inside a 40 ft container).

Fig. 1. Constructed brackish water RO unit which is developed as a pilot for this study.

An SWRO unit with the same capacity as the BWRO unit, shown in Fig. 1, has also been built. The results obtained through simulation in this paper have a good accuracy compared to laboratory results. Table 1 shows the information of the pilot system.

Table 2 shows the detailed information of considered scenarios. The prime cost of electrical energy is 5.6 US$ cent for the government; the average tariff of electrical energy for industrial activity is 1.4 US$ cent, and this value for desalination unit is 0.5 US$ cent. Finally, in this article, the real prime cost of electrical energy is used as energy inlet price.

For better investigation, five different climates are chosen. The geographical position, and also, the quality of inlet raw water in selected cities are presented in Table 3. Due to the access to seawater and brackish water in Rasht and Jask both reverse osmosis technology (BWRO) and (SWRO) are studied.

3. System simulation and analyses

3.1. Reverse osmosis desalination unit

In this section, a simplified method for simulation of reverse osmosis desalination unit is presented. In this

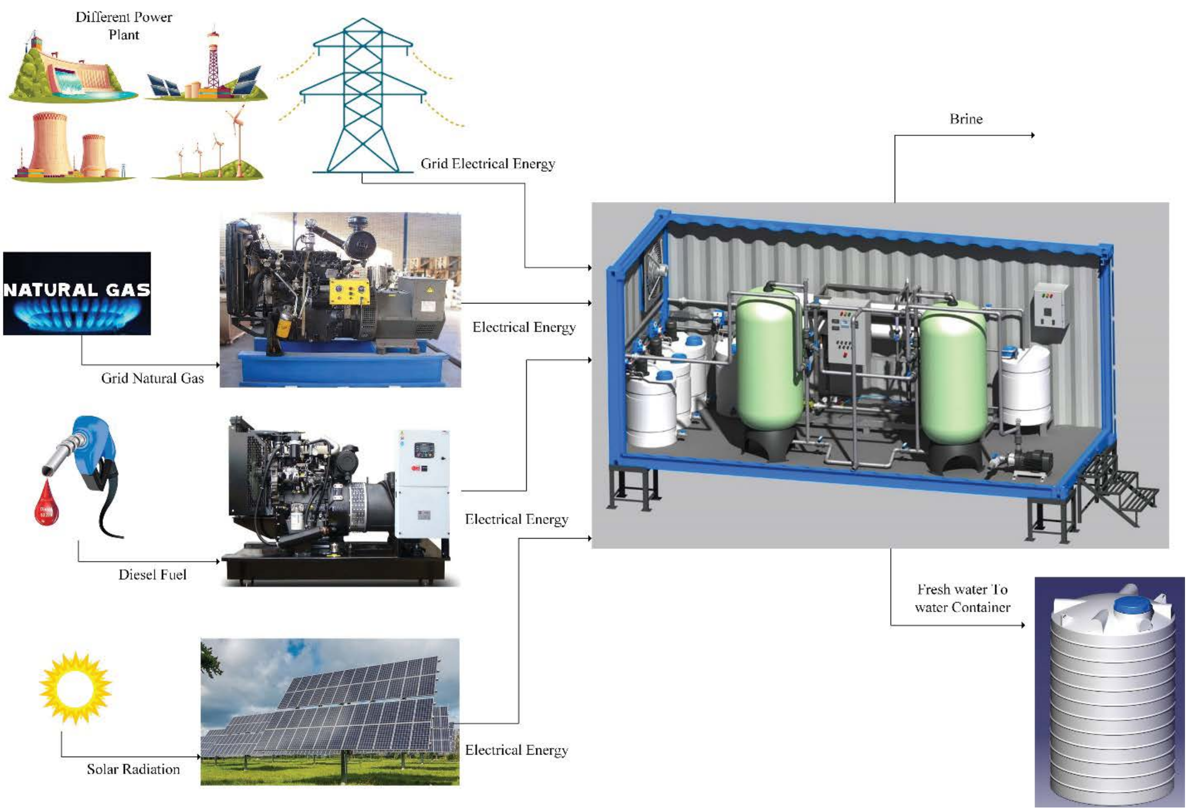


Fig. 2. Different energy supplier for the considered scenarios.

method, the feed water, permeate, and brine are identified by the subscript of *f*, *p*, and *b*, respectively. One of the important parameters is the osmotic pressure, which is the function of temperature and salt concentration in the feed water [22]. If we want to have a positive permeate flow, the operating pressure should be greater than the osmotic pressure. The main relations that are used in the presented RO modeling are mentioned in Table 4.

Table 1
Details information of RO unit

Parameter	Value
Maximum TDS of feed water (ppm)	5,000
Maximum capacity of freshwater production (m^3/d)	120
Maximum pressure (bar)	18
Membrane numbers	4
Membrane type	BW8040 (BW30400)

Table 2
Information of considered scenarios

Scenarios	Inlet energy source to RO unit	Required fuel for inlet energy
Reference	Grid	Natural gas and liquid fuel
Number 1	Gas engine	Natural gas
Number 2	Diesel engine	Diesel
Number 3	Solar PV	–

Table 3
Geographical position and also the quality of inlet row water in selected cities [21]

City	Latitude	Longitude	Inlet TDS (ppm)	RO Type (BW or SW)
Rasht (1)	37.28	49.58	2,000	BWRO
Rasht (2)	37.28	49.58	18,000	SWRO
Tehran	35.69	51.42	2,000	BWRO
Semnan	35.57	53.39	3,500	BWRO
Yazd	31.89	54.36	5,000	BWRO
Jask (1)	25.65	57.78	4,000	BWRO
Jask (2)	25.65	57.78	40,000	SWRO

Table 4
Relations that used in reverse osmosis modeling [23,24]

Relation	Description	Number
$\text{SEC} = \frac{\Delta P}{Y} = \frac{P_{\text{sys}}}{Y}$	The specific energy consumption (SEC) defined as the electrical energy needed to produce a cubic meter of permeate (P_{sys} and Y are working pressure and water recovery factor)	(1)
$P_{\text{sys}} = \frac{\rho A_p}{A_m K_m}\left(V_f - V_r\right) + \Delta\pi$	Working pressure (v_r is the retentate stream velocity, A_p is the pipe cross sectional area, A_m is the active membrane surface area, k_m is the overall mass transfer coefficient, V is the system volume, v_f is the feed stream velocity, ρ is the fluid density)	(2)
$Y = \frac{Q_p}{Q_f}$	Permeate product water recovery for the RO process (for BWRO and SWRO units the water recovery is assumed to be 50% and 25%, respectively)	(3)
$\Delta\pi = f_{\text{os}} C_{\text{feed}} \frac{\ln\left(\frac{1}{1-Y}\right)}{Y}$	Osmotic pressure difference across the surfaces of the membrane (f_{os} is an empirically obtained constant ($f_{\text{os}} = 78.7$) [24,25])	(4)
$Q_p = \frac{E_{\text{PV}}}{\text{SEC}}$	Product flow rate (Q_p) can be extracted by E_{PV} (energy of photovoltaic)	(5)

3.2. Gas engine and diesel engine

The small-scale Iranian gas engines are used in this study. The sizes of gas engines are 33 and 55 kVA and these engines are manufactured by Motorsazan Company, which is located in Sardrood, I.T. Co. Complex, Motorsaza Co., Tabriz-Iran, (MN440A-45GN with maximum power 33 kVA and 4 cylinders, and MN660A-70GN with maximum power 55 kVA and 6 cylinders). The magnitude of engine bore, stroke, and compression ratio for 33 and 55 kVA are similar and equal to 100, 127 mm, and 9.5:1, respectively [25]. It should be noted that the operational thermodynamic cycle of the engine is Otto and the required natural gas pressure for these engines is 0.25 psi.

The detailed simulation of the gas engine is not subjected in this study but a correlation between the generated power and the natural gas consumption is presented as follow [26]:

$$\text{Natural gas consumption rate} = 0.386 \times \text{Generated power}(\text{kW}) + 3.78 \quad (6)$$

For the diesel engine, the procedure is identical. The capacities of Iranian diesel engines used in this study are 45 and 72 kVA [26]. Eq. (7) shows the relationship between the produced power and the amount of diesel fuel consumption. This relationship is generated by the company's testing engine lab.

$$\text{Diesel fuel consumption rate} = 0.261 \times \text{Generated power}(\text{kW}) - 0.2 \quad (7)$$

3.3. Solar radiation modeling

The amount of solar energy on tilted surface is estimated by the following equations [27,28]:

$$\bar{I}_T = \bar{K}_T \bar{H}_0 \left[\left(r_t - \frac{\bar{H}_d}{\bar{H}} r_d \right) R_b + \frac{\bar{H}_d}{\bar{H}} r_d \left(\frac{1+\cos\beta}{2} \right) + \rho_g r_t \left(\frac{1-\cos\beta}{2} \right) \right] \quad (8)$$

where

$$r_t = \frac{\pi}{24}(a + b\cos\omega) \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \quad (9)$$

$$r_d = \frac{I_d}{H_d} = \frac{\pi}{24} \left(\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \right) \quad (10)$$

and

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \quad (11)$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \quad (12)$$

3.4. Solar PV modeling

Current and voltage under arbitrary conditions can be obtained using the following relation [29].

$$I_{SC}(G) = \frac{I_{SC}^*}{G^*} G_{eff} + (T_C - T_C^*) \mu_{I_{sc}} \quad (13)$$

$$V_{OC_{PV}}(T_C) = V_{OC_{PV}}^* + (T_C - T_C^*) \frac{dV_{OC_{PV}}}{dT_C} + V_t \ln\left(\frac{G_{eff}}{G^*}\right) = V_{OC_{PV}}^* + (T_C - T_C^*)\mu_{V_{OC}} + V_t \ln\left(\frac{G_{eff}}{G^*}\right) \quad (14)$$

The technical data of solar PV panel with capacity of 250 W is presented in Table 5.

The generated energy from the solar PV system is stored in lithium-ion battery pack using a charge controller. When the electrical energy is needed, the stored energy is converted from DC to AC using an inverter. The efficiency of the charge controller and the inverter is assumed to be 95%, and the battery pack can be discharged up to 80%.

3.5. Economic analyses

ACS is chosen as the economic method in this study [29]:

$$\text{ACS} = C_{acap} + C_{arep} + C_{amain} + C_{aope} \quad (15)$$

Table 6 shows the relations and data that are needed for economic analysis. Also, Table 7 shows the instrument capital cost and other economic assumptions [30–35].

Total efficiencies of the main pumps of BWRO and SWRO systems are assumed 75% and 50%, respectively.

3.6. Environmental analysis

The amounts of emission and greenhouse gases generated in each scenario are given in Table 8. Based on them and the following relation, penalty cost is calculated and presented in Table 8. These penalty costs are considered in the economic results section as one of the costs of the system and presented in separate figures. The emission unit in relation 16 is presented in tone scale [36–38].

Table 5
Technical data of solar array

Parameter	Magnitude	Parameter	Magnitude
Short-circuit current [A], I_{SC}	8.7	Nominal output [W], P_{mpp}	250
Open-circuit voltage [V], V_{OC}	37.8	Voltage/temperature coefficient [V/°C], $\mu_{V_{oc}}$	–0.351
Nominal current [A], I_{mpp}	7.94	Current/temperature coefficient [A/°C], $\mu_{I_{sc}}$	0.053
Nominal voltage [V], V_{mpp}	31.5	Number of series cell, N_S	60

Table 6
Economic analysis relations and assumptions [30–35]

Parameter	Formula
Annualized capital cost	$C_{acap} = C_{cap} \cdot \frac{i \cdot (1+i)^{Y_{proj}}}{(1+i)^{Y_{proj}} - 1}$
Net present value (NPV)	$NPV = ACS \cdot \frac{(1+i)^{Y_{proj}} - 1}{i \cdot (1+i)^{Y_{proj}}}$
Annualized cost of system (ACS)	$ACS = C_{acap} + C_{arep} + C_{amain} + C_{aope}$
Levelized cost of product (LCOP)	$LCOP = \frac{\text{ACS-(Income from heat recovery)}}{\text{Annual output product of the system}}$
Annual real interest rate	$i = \frac{(j - f)}{(1 + f)}$
Operating flow cost (OFC)	Fuel cost + MC + Labor cost + Insurance cost + Chemical cost for RO
Prime cost (PC)	$PC = \frac{(OFC)}{(VOP)}$
Summation of product cost (SPC)	$SOPC = VOP \times (\text{Price of product}(POP))$
Annual benefit (AB)	$AB = SOPC - OFC$
Net annual benefit (NAB)	$NAB = AB - TAX$
Rate of return	$ROR = \frac{(\text{Net annual benefit})}{(\text{Capital cost})}$
Period of return	$POR = \frac{(\text{Capital cost})}{(\text{Net annual benefit})}$
Additive value (AV)	$AV = POP - PC$
Assumption which is used in this economic study (January 2018) [35]	
Year of project	15 y
Inflation rate (%) (f)	10%
Nominal interest rate (%) (j)	15%
Rate of insurance cost (%)	2%
Tax cost	10%
Maintenance cost (spare part) for desalination unit and power suppling system	6.5% of capital cost/y
Required chemical material cost for desalination unit cost	7 US$ cent per cubic meter of fresh water
Labor cost	400 US$/month
Number of labor	Two persons in considered scenarios except PV application
Number of labor	Three persons in solar PV application in desalination plant
Operating h/y	8,760 h
System availability for BWRO unit	80%
System availability for SWRO unit	65%
Exchange rate (Rials equal to one US$)	85,000
Price of electrical energy, natural gas, and diesel fuel [33]	
Electrical energy (grid) (without any subsidy)	5.7 US$ cent/kWh
Natural gas price (without any subsidy)	14 US$ cent/m^3
Diesel fuel price (without any subsidy)	80 US$ cent/L

Table 7
Instrument capital cost and the other economic assumption [30,31]

Equipment	Capital cost
BWRO unit	Price of each membrane for 8 inch size = 500US$ Price of each pressure vessel for 8 inch size = 150US$ $\text{Pump price (Main pump. coupling and drive motor)} = 705.48 \times P_{\text{pump}}^{0.71} + \left(1 + \frac{0.2}{1-\eta_{\text{pump}}}\right)$ Dosing pump (for CL. Anti scalant. metabisulphite) = 500 US$ per dosing pump $\text{CIP (Claen in place pump price) and feed pump} = 705.48 \times P_{\text{pump}}^{0.71} + \left(1 + \frac{0.2}{1-\eta_{\text{pump}}}\right)$ Container cost (20 ft) = 20,000 US$ Main component costs (MCC) = Main pump. membrane. Pressure vessel. dosing pump. CIP pump and container price Pre treatment cost (Sand filter. carbon filter. micro filter) = 0.5(MCC) Manufacturing cost (Structure and piping) = 0.45(MCC) Contol system cost (Control box and actuators) = 0.3(MCC)
SWRO unit	Price of each membrane for 8 inch size = 850 US$ Price of each pressure vessel for 8 inch size = 255 US$ $\text{Pump price (Main pump. coupling and drive motor)} = 705.48 \times P_{\text{pump}}^{0.71} + \left(1 + \frac{0.2}{1-\eta_{\text{pump}}}\right)$ Dosing pump (for CL. anti scalant. metabisulphite) = 500 US$ per dosing pump $\text{CIP (Claen In Place Pump Price) and Feed Pump} = 705.48 \times P_{\text{pump}}^{0.71} + \left(1 + \frac{0.2}{1-\eta_{\text{pump}}}\right)$ Container cost (40 ft) = 35,000 US$ Main component costs (MCC) = Main pump. membrane. Pressure vessel. dosing pump. CIP pump and container price Pre treatment cost (Sand filter. Carbon Filter. Micro Filter) = 0.5 (MCC) Manufacturing Cost (Structure and Piping) = 0.45 (MCC) Contol system cost (Control box and actuators) = 0.3(MCC)
Gas engine (33 kVA)	7,140 US$
Gas engine (55 kVA)	12,000 US$
Diesel engine (up to 140 kVA)	133 US$/kW
Solar PV (off grid system)	3,040 US$ per kW (33% for PV Panel, 13% for structure, 20% for charge controller, 14% for inverter, and 20% for cabling and construction)
Battery price (lithium ion)	400 US$/kWh

Table 8
Magnitudes of pollutant and greenhouse gases generated by each input energy source [36–38]

Energy input technology	Grid power	Gas engine	Diesel engine	Solar PV
CO_2 production (g/kWh)	645.98	836.92	815.11	0
NO_x production (g/kWh)	2.413	2.083	1.504	0
SO_2 production (g/kWh)	1.113	0	4.611	0
Penalty cost (US$/kWh)	0.383	0.34	0.259	0

$$\text{Penalty cost of emission} = 40\left(m_{CO_2}\right) + 147.582\left(m_{NO_x}\right) + 970\left(m_{SO_2}\right) \quad (16)$$

3.7. System sizing

Sizing of the components is considered in this section. For gas engine and diesel engines the available Iranian engines are selected according to the requested power and the engine size inventory. In order to determine the appropriate size of components of the solar system, first, the annual amount of required energy with respect to the battery, the charge controller, and the invertor losses is calculated. The energy losses in the lithium battery pack, inverter, and charge controller are assumed 20%, 5%, and 5%, respectively. Then based on the solar radiation in each city and annual electricity generation by a 1 kW solar PV panel, the required number of panels is determined. The charge controller size is designed regarding the maximum generation current of the solar system and the size of the lithium battery is chosen to store the whole generated energy over 1 d. It should be noted that the depth of discharge (DOD) is assumed 80%. Finally, the inverter size is chosen based on the maximum required power from the desalination unit. Energy recovery in desalination systems is highly important, especially for SWRO systems, which includes a high-pressure pump. Using different methods such as a pressure exchanger can recover plenty of energy. Lastly, a proper design for water distribution to the consumer should be desalinated.

This article consists of several steps, which are illustrated in Fig. 3.

4. Results and discussion

4.1. Reverse osmosis unit's specification

Table 9 shows the specification of the RO units (BWRO and SWRO) with a capacity of 100 m^3/d freshwater generations. Total power consumption includes the main pump power, the feed pump power, the dosing pump power, and the other power consumption. The whole other power consumptions are assumed to be 20% of the summation of the main pump, the feed pump, and the dosing pump powers.

4.2. Parametric study of the desalination unit

In this study, three parameters (main pump power consumption, inlet feed water required pressure, and specific energy consumption per unit of freshwater production) are considered. In two cases (BWRO and SWRO unit), the variations of considered parameters in different inlet water salinity and system recovery are studied. Fig. 4 shows the results of this parametric study.

Table 9
Specification of considered RO units (BWRO and SWRO)

Brackish water reverse osmosis desalination unit (inlet water salinity is 5,000 ppm)			
Water recovery (Percent)	Number of membrane	Size of membrane and selected model	Total power consumption (kW)
50	7	8 inches (BW30–400)	8.87
55	7	8 inches (BW30–400)	9.03
60	7	8 inches (BW30–400)	9.30
65	7	8 inches (BW30–400)	9.63
70	7	8 inches (BW30–400)	10.05
Sea water reverse osmosis desalination unit (inlet water salinity is 45,000 ppm)			
Water recovery (%)	Number of membrane	Size of membrane	Total power consumption (kw)
25	8	8 inches (SW30HRLE-400)	40.51
30	8	8 inches (SW30HRLE-400)	42.45
35	8	8 inches (SW30HRLE-400)	45.02
40	8	8 inches (SW30HRLE-400)	48.25
45	8	8 inches (SW30HRLE-400)	52.30

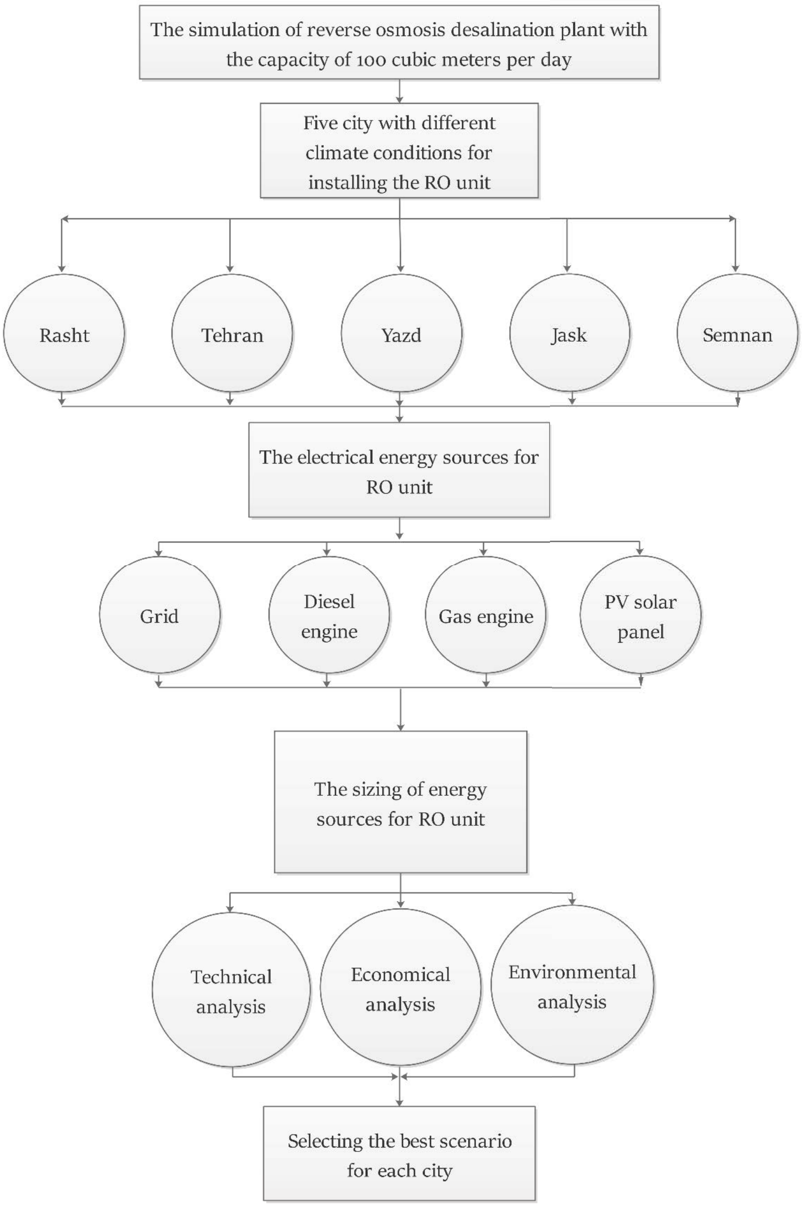


Fig. 3. Flowchart of the calculations.

More investigation shows that the variations are nonlinear. As can be seen, by increasing the amount of inlet water salinity, and also, by increasing the water recovery in the desalination unit, the main pump power consumption, inlet water required pressure, and the specific energy consumed per cubic meter of freshwater increase too. These changes in seawater units are sharper than in brackish one. It should be noted that the structure of desalination units is assumed to be constant in this study.

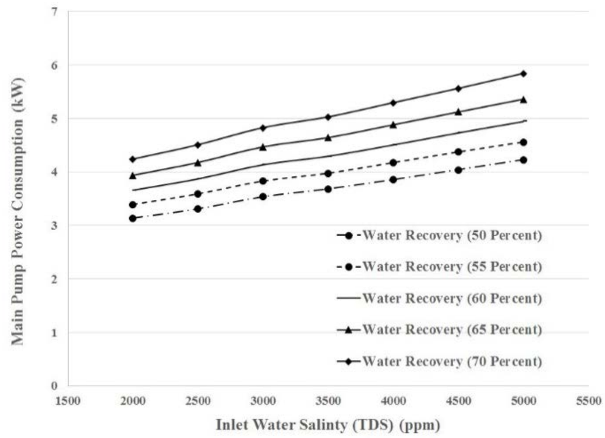
4.3. Monthly solar energy production in selected cities

Using the relation presented in the simulation section, Fig. 5 shows the monthly energy production from 1 kW (four solar panel with the capacity of 250 W) solar PV panels and in selected cities. All the calculations are performed using MATLAB software.

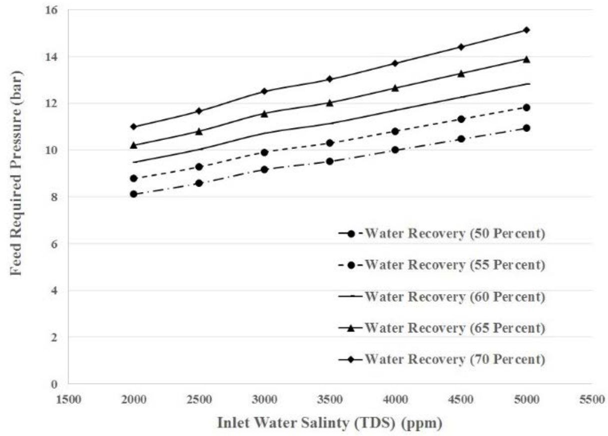
Results show that Yazd has the best energy production, and Rasht has the worst one. It also shows that Tehran and Semnan are similar in solar energy production.

4.4. Size of system in considered scenarios

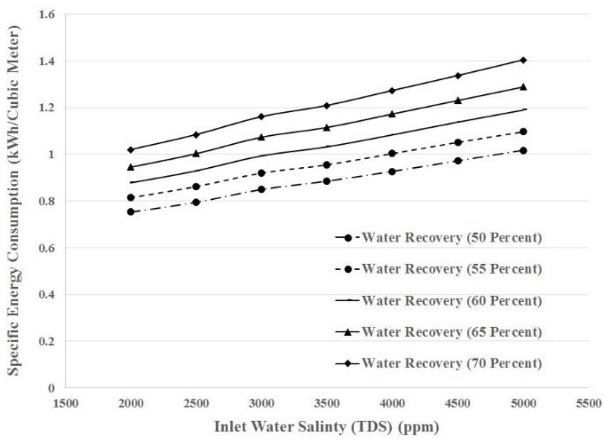
The specifications of the components and their capacities are presented in Table 10. According to statistics, in each of the installation points of the desalination plant, a population of about 20,000 people is considered. By considering that the average consumption of freshwater per person during the day is between 2 and 5 L, the production capacity of freshwater is considered to be 100,000 L/d in SWRO



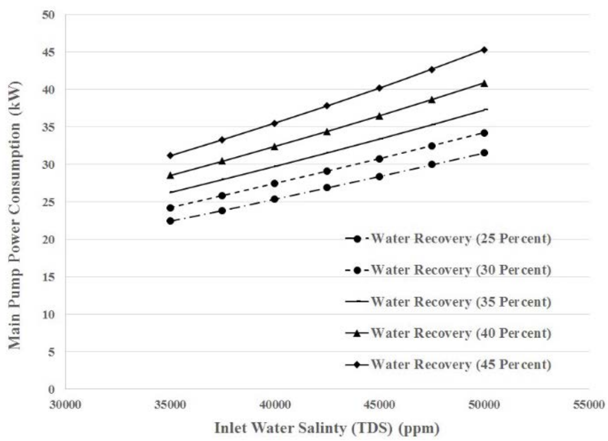
BWRO Unit (main pump power)



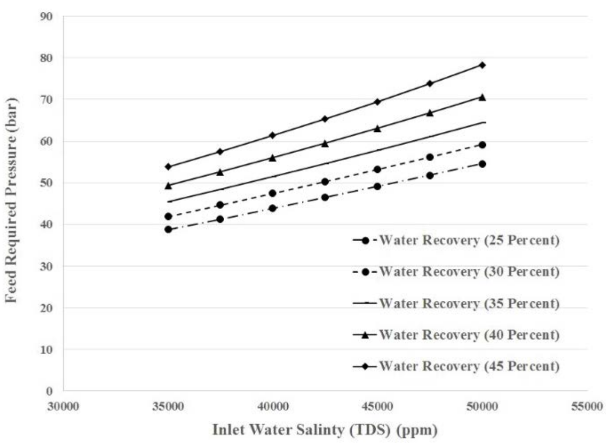
BWRO Unit (feed required pressure)



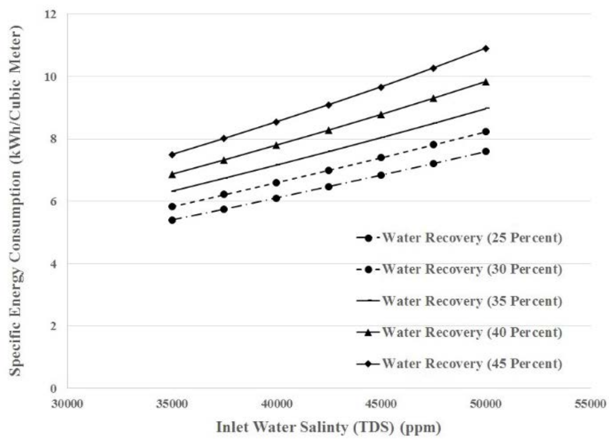
BWRO Unit (specific energy consumption)



SWRO Unit (main pump power)



SWRO Unit (feed required pressure)



SWRO unit (specific energy consumption)

Fig. 4. Results of the parametric study in desalination unit.

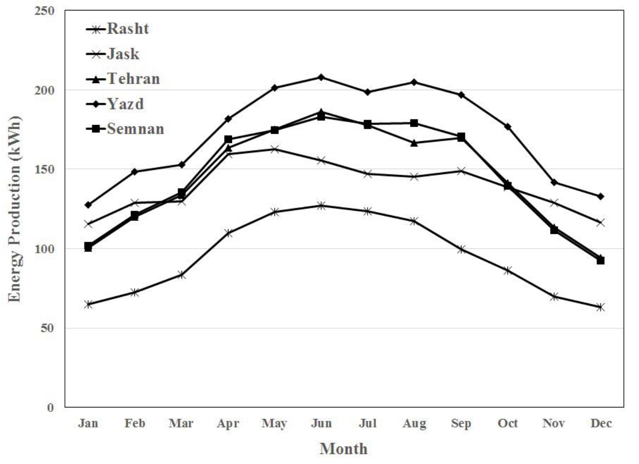


Fig. 5. Monthly energy production from 1 kW solar PV panels and in selected cities.

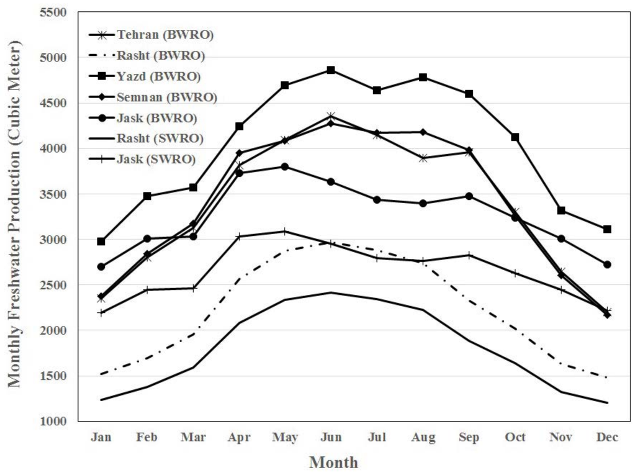


Fig. 6. Monthly freshwater production in selected cities via solar PV energy input.

and BWRO unit to supply high-quality water. The amount of electrical energy consumption in each unit is calculated through simulation, and then suitable engines are chosen to provide power consumption regarding the available gas engines and diesel engines. Also, in order to determine the size of the solar panels and the battery bank, the information in the previous article in this field has been used [39].

4.5. Freshwater production via solar PV energy system in selected cities

In this section, according to the system's sizes and the amount of energy production in selected cities, the monthly freshwater production is calculated and presented as Fig. 6.

As shown in Fig. 6, the highest freshwater production is desalinated in Yazd by BW desalination unit; the lowest amount of freshwater production is desalinated in Rasht by the SW desalination system. It is also observed that freshwater productions in Tehran and Semnan cities have a similar trend.

4.6. General results of economic analysis

According to the economic assumptions, which are presented in Tables 6 and 7, Table 11, and Fig. 7 shows the general results of economic analysis for considered scenarios. The natural gas and gas-oil prices are assumed to be 14 US$ cent/m^3 and 80 US$ cent/L, respectively [40].

Also, two important parameters (LCOP and PC) are calculated for considered scenarios and presented in Fig. 7.

Furthermore, while the initial capital costs of the renewable power system (solar system in this study) are higher than fossil-fueled power plants, these plants have lower

Table 10
Specification and size of proposed system's components

Rasht (BWRO) system			
Scenario 1	Scenario 2	Scenario 3	
Gas engine size (kVA)	Diesel engine size (kW)	Solar PV size (kW)	Battery pack size (kWh)
33 kVA	45 kVA	55	230
Rasht (SWRO) system			
55 kVA × 2	72 kVA	313	1,325
Tehran (BWRO) system			
33 kVA	45 kVA	36	220
Semnan (BWRO) system			
33 kVA	45 kVA	39	237
Yazd (BWRO) system			
33 kVA	45 kVA	39	265
Jask (BWRO) system			
33 kVA	45 kVA	42	227
Jask (SWRO) system			
55 kVA × 2	72 kVA	363	1,967

Table 11
General results of economic analyses in considered scenarios and in selected cities

Scenarios	Total capital cost (US$)	ACS (US$)	NPV (US$)	POR (US$) freshwater cost (XXX US$/m^3)	Operating cost (US$)	Maintenance cost (US$)
Rasht (BWRO) system, inlet TDS (2,000 ppm), water recovery (50%)						
Reference	39,112.30	22,359.38	239,380.9	6.35 (0.8)	17,937.36	1,814.53
Scenarios 1	55,281.21	25,992.23	278,274.5	6.36 (0.8)	19,222.16	3,084.65
Scenarios 2	50,780.96	29,694.15	317,907.5	–(0.8)	23,641.65	2,667.98
Scenarios 3	403,003.68	79,007.52	845,859.5	–(0.8)	23,196.78	28,943.83
Rasht (SWRO) system, inlet TDS (18,000 ppm), water recovery (25%)						
Reference	78,626.63	36,952.49	395,615.7	–(6.5)	28,063	3,647.72
Scenarios 1	125,024.64	69,348.09	742,445.1	1.2 (6.5)	53,060.31	7,952.8
Scenarios 2	89,359.99	76,611.72	820,210	–(6.5)	66,010.77	4,643.62
Scenarios 3	2,152,889.25	350,416.7	3,751,583	–(6.5)	47,792.71	159,098
Tehran (BWRO) system, inlet TDS (2,000 ppm), water recovery (50%)						
Reference	44,072.61	20,796.17	222,645.1	6.35 (0.8)	15,813.34	2,044.65
Scenarios 1	55,281.21	25,992.23	278,274.5	6.36 (0.8)	19,222.16	3,084.65
Scenarios 2	50,780.96	29,694.15	317,907.5	–(0.8)	23,641.65	2,667.09
Scenarios 3	318,320.31	65,806.75	704,531.2	–(0.8)	21,987.94	22,597.45
Semnan (BWRO) system, inlet TDS (3,500 ppm), water recovery (50%)						
Reference	45,161.99	21,196.93	226,935.6	7.55 (0.8)	16,090.93	2,095.19
Scenarios 1	56,370.6	26,413.24	282,781.8	6.83 (0.8)	19,520	3,135.19
Scenarios 2	51,870.34	30,487.69	326,403.2	–(0.8)	24,312.03	2,717.63
Scenarios 3	342,614.89	69,562.78	744,743.5	–(0.8)	22,334.74	24,387.04
Yazd (BWRO) system, inlet TDS (5,000 ppm), water recovery (50%)						
Reference	46,205.25	21,591.81	231,163.3	7.55 (0.8)	16,367.86	2,143.59
Scenarios 1	57,413.86	26,828.37	287,226.2	7.34 (0.8)	19,817.18	3,183.59
Scenarios 2	52,913.6	31,288.87	334,980.6	–(0.8)	24,995.26	2,766.03
Scenarios 3	357,738.77	71,890.56	769,664.9	–(0.8)	22,550.63	25,490.68
Jask (BWRO) system, inlet TDS (4,000 ppm), water recovery (50%)						
Reference	45,497.37	21,322.72	228,282.4	7.11 (0.8)	16,178.8	2,110.75
Scenarios 1	56,705.97	26,545.45	284,197.2	6.98 (0.8)	19,614.29	3,150.75
Scenarios 2	52,205.72	30,740.85	329,113.4	–(0.8)	24,527.27	2,733.19
Scenarios 3	350,506.76	70,783.42	757,811.8	–(0.8)	22,447.4	24,968.91
Jask (SWRO) system, inlet TDS (40,000 ppm), water recovery (25%)						
Reference	97,910.86	49,775.72	532,902	0.79 (6.5)	38,705.95	4,542.37
Scenarios 1	144,308.87	81,413.93	871,622.7	1.74 (6.5)	62,945.89	8,847.45
Scenarios 2	108,644.22	116,449.1	1,246,712	3.5 (6.5)	103,667.9	5,538.27
Scenarios 3	2,751,546.71	443,184.5	4,744,761	–(6.5)	56,338.39	203,409.6

operating flow cost than fossil fuel-powered systems. Fig. 8 illustrates the ratio of the annualized capital cost of the system to its annualized operating and flow costs in the different scenarios.

More studies show that the lowest ratio of annualized capital costs to operating flow costs is seen in diesel engine powered systems and the highest one is belonging to the solar PV powered systems. However, this ratio is almost the same in the gas engine and grid-powered systems.

4.7. Sensitive analyses of economic parameters

4.7.1. Variation of period of return during the variation of freshwater price

In this section, the variation of the period of return with respect to the changes in the freshwater price is shown in Fig. 9.

The results show that the variation of the period of return of BW system is similar to each other. It is also

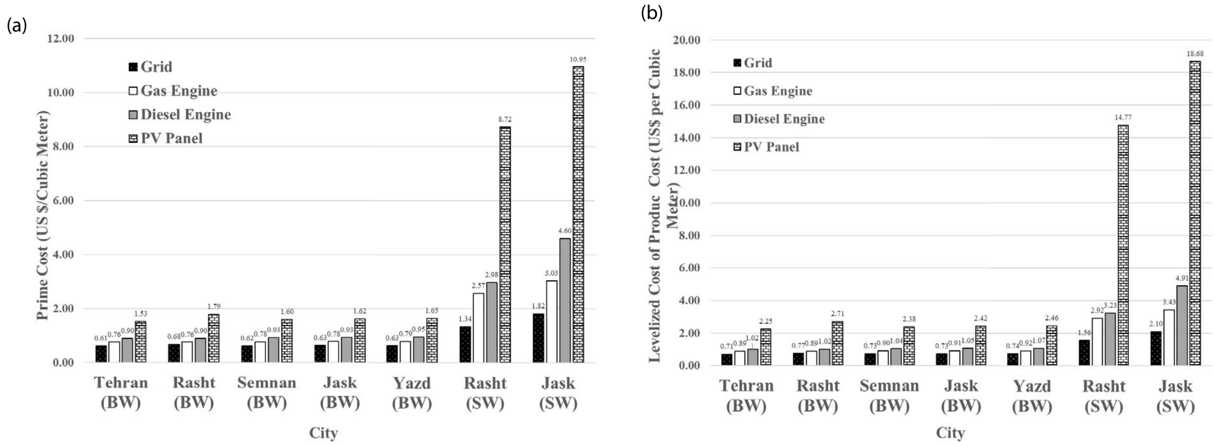


Fig. 7. LCOP and PC (economic parameter) for considered scenarios. (a) Levelized cost and (b) prime cost of product in considered scenarios.

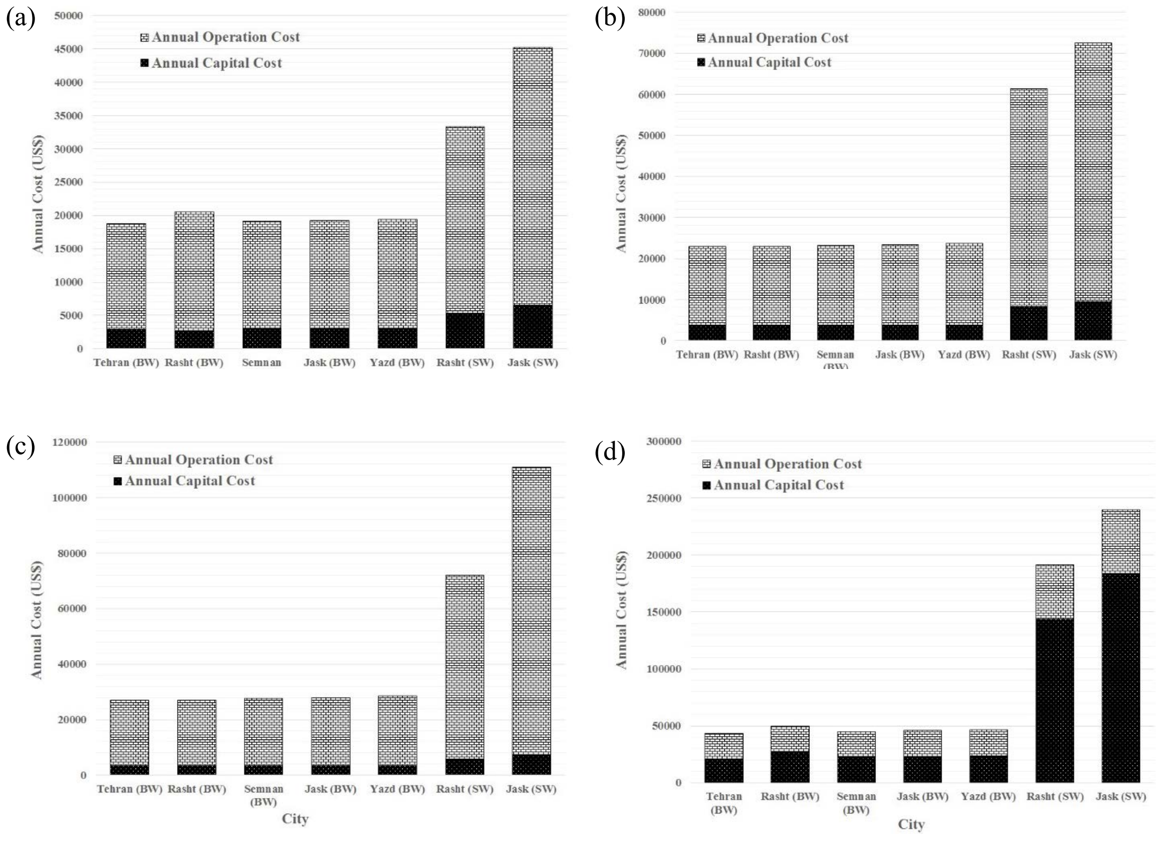


Fig. 8. Ratio of the annualized capital cost of system vs. its annualized operating and flow costs in different scenarios. Input energy from (a) grid power, (b) gas engine, (c) diesel engine, and (d) solar PV.

observed that freshwater price should be much higher in SW systems compared to BW systems so that system will be economical. Obviously, the higher level of TDS, the less economical the system is. Also, the difference between SW system in Rasht and in Jask becomes more significant when photovoltaic panel are used. This is because the initial cost grows more sharply than flow costs.

4.7.2. Effect of the amount of solar power and water price on system economic

In order to economically evaluate the application of solar energy (PV) for the purpose of producing freshwater through reverse osmosis unit, the amount of generated energy by 1 kW solar PV panel in each region has

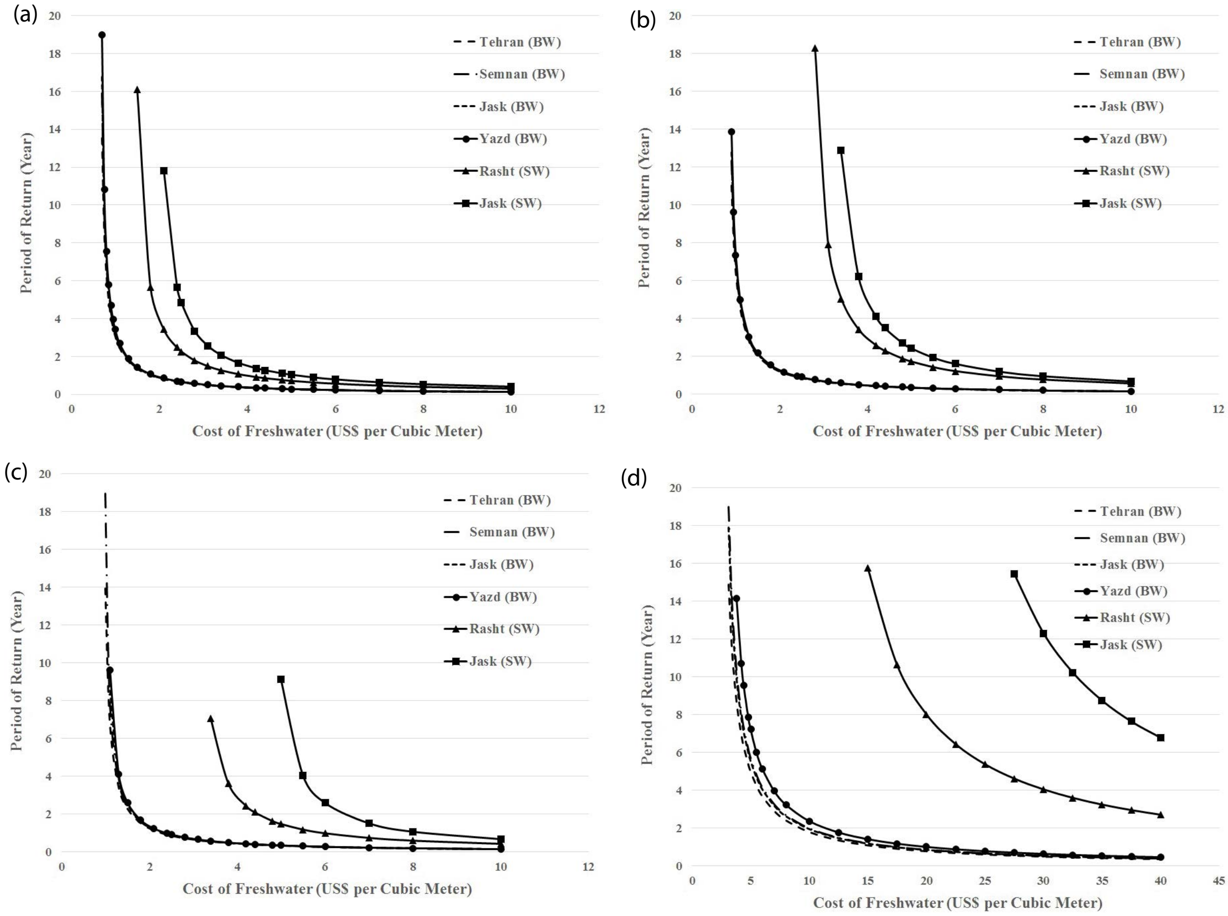


Fig. 9. Variation of the period of return in the considered scenarios with the changes in the freshwater price. Input energy from (a) grid power, (b) gas engine, (c) diesel engine, and (d) solar PV.

been selected as the criterion. Fig. 10 shows the period of return of desalination plant variation at different amount of energy production via one kW solar PV panel. The ranges of freshwater prices for BWRO and SWRO units are assumed to be 2.5–10 and 12–30 US$/m^3, respectively.

The results show that BW systems are mostly feasible when even solar energy production is not high. In the BWRO unit with freshwater price of 5 US$/m^3 and more, the considered system is economically feasible at different solar PV energy output. This magnitude for SWRO unit is calculated

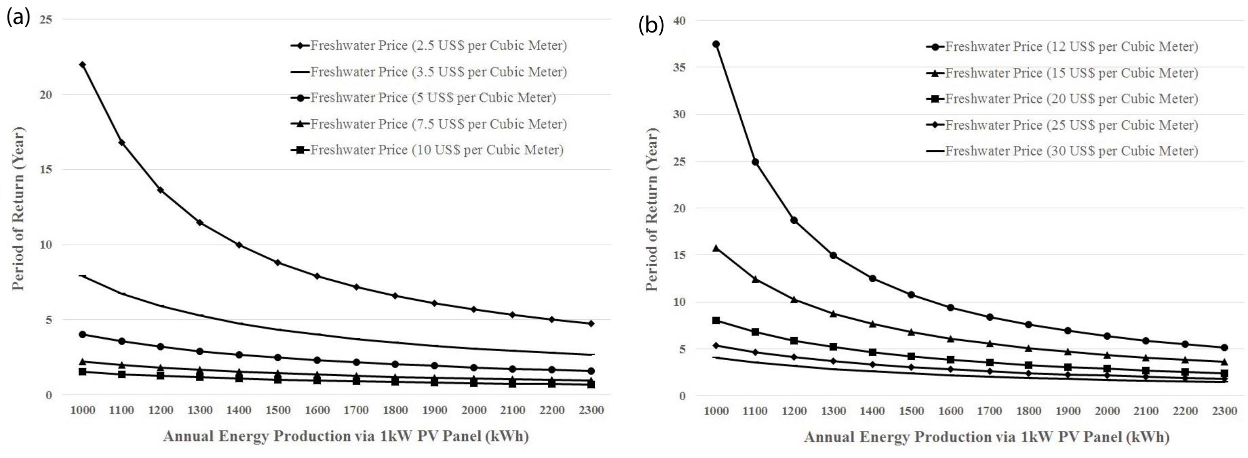


Fig. 10. Period of return of desalination plant variation during the amount of energy production via one kW solar PV panel. (a) BWRO and (b) SWRO unit.

as 20 US$/m. It should be noted that the annually generated energy via 1 kW PV panels in selected cities is within range of 1,140 kWh (Rasht) to 1,947 kWh (Yazd).

4.7.3. Minimum price of energy utility to make the systems economically feasible

The period of return of 5 y is recognized as an acceptable limit for economic feasibility in water and energy projects within the country. According to this fact, the minimum price of energy utility (electrical energy from grid, natural gas, and diesel fuel) is calculated in the scenarios to make POR 5 y. Table 12 shows the results of this investigation.

4.7.4. Minimum freshwater price to make the considered system economically feasible

Fig. 10 shows the minimum freshwater price that makes the period of return 5 y. Electricity price, natural gas price, and diesel fuel price are assumed to be 5.7 US$/kWh, 14 US$/m^3, and 80 US$/L, respectively.

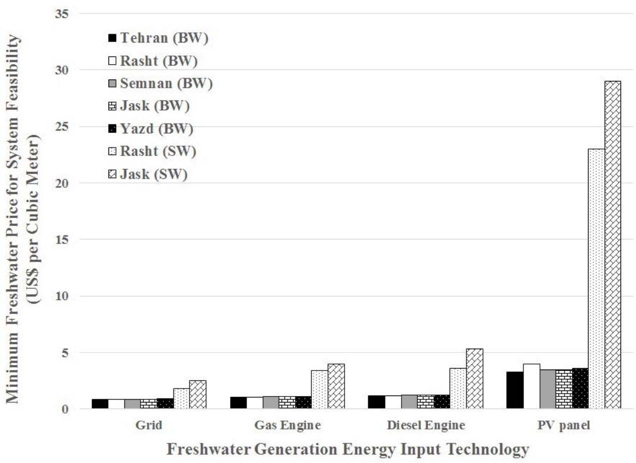


Fig. 10. Minimum freshwater price to make the considered system economically feasible.

4.8. Effect of environmental penalty cost on the economic feasibility of solar powered units

As mentioned in section 3.6 (Environmental analysis), the environmental impact of different power generation technology can be calculated. In this section, it is assumed that the average of emission penalty cost in other scenarios will be allocated to the freshwater generation from solar PV in order to support the nature friendly systems. Fig. 11 shows the results of this investigation. The results show that allocating this subsidy to BWRO units reduces the period of return by 13.75% and 17.5% in Rasht and Yazd, respectively. Also, in SWRO unit, it is reduced by 18.7% in Rasht and 26.9% in Jask.

5. Conclusion

Water scarcity is one the most serious crisis in the world. It is even more intensive in middle-east, especially in Iran. In this study, the reverse osmosis system with different energy suppliers including gas engine generator, diesel engine generator, and solar PV panel is studied in terms of technical, economic, and environmental. Technical results show that the increment in inlet water TDS raises the required pressure, power consumption, and specific energy consumption. According to the assumptions, among the energy suppliers considered in this study, gas engine is found to be the most economical although capital cost of diesel engine is lower than the other power suppliers. For the system powered by gas engine, POR and LCOP are in range of 6.35–7 y and 0.89–0.92 US$/m^3 for BWRO, and 1.2–1.74 y and 2.92–3.43 US$/m^3 for SWRO. On the other side, the amounts of LCOP of freshwater via RO unit that is powered by solar PV panel are within range of 2.25–2.7 and 14.77–18.68 US$/m^3 in BWRO and SWRO system, respectively. Furthermore, variation of POR with respect to annual energy production via solar PV panel illuminates the minimum values to make the system economically feasible. It also shows that in the BWRO unit, and for the freshwater price of 5 US$/m^3 (and more), the considered system is economically feasible at different solar PV energy output. This magnitude for SWRO unit is calculated as 20 US$/m^3.

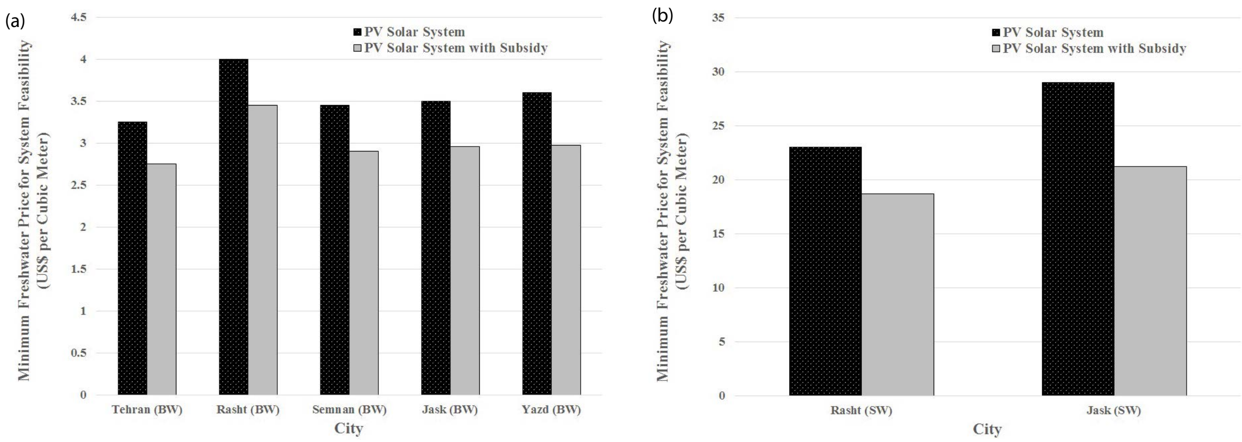


Fig. 11. Effect of environmental penalty cost on the economic feasibility of solar-powered units. For (a) brackish water unit and (b) sea water unit.

Table 12
Minimum price of energy utility to make the considered system economically feasible (POR = 5 y)

	Tehran (BWRO)	Rasht (BWRO)	Yazd (BWRO)	Semnan (BWRO)	Jask (BWRO)	Rasht (SWRO)	Jask (SWRO)
Freshwater price			(1 US$) for BWRO			(3 US$) for SWRO	
Diesel fuel price (US$)	0.4	0.4	0.33	0.36	0.36	0.59	0.31
Natural gas price (US$)	0.095	0.095	0.078	0.085	0.085	0.106	0.072
Electricity from grid (US$)	0.16	0.16	0.12	0.14	0.14	0.162	0.085

Eventually, since the only environmental friendly scenario is PV-RO, and regarding emissions of other systems (CO_2, NO_x, and SO_2), a subsidy is allocated to solar panel system to improve its economic feasibility. The results show that allocating this subsidy to BWRO units reduces the period of return by 13.75% and 17.5% in Rasht and Yazd; in SWRO unit, it reduces by 18.7% and 26.9% in Rasht and Jask.

According to the results of this paper, following issues seem to need further studies and investigation. Firstly, the desalination system and its energy supplier systems can be optimized with respect to water consumption pattern in each location. Secondly, the solutions for brine effluents of systems should be assessed in order to increase system sustainability. Furthermore, energy recovery in desalination systems is highly important, especially for SWRO systems, which includes high pressure pump. Using different methods such as pressure exchanger can recover plenty of energy. Lastly, a proper design for water distribution to consumer should be studied.

Symbols

I_T — Solar radiation, MJ/m²
K_T — Clearness index
H_d — Monthly average daily radiation on horizontal surface, MJ/m²
H_0 – Average clear-sky daily radiation, MJ/m²
R_b — Solar radiation index
ρ_g — Reflection factor
ω — Hourly angle, rad
ω_s — Sunset hourly angle, rad
β — Altitude angle, rad
I_{SC} — Short circuit of solar panel, A
V_{OC} — Open circuit of solar panel, V
T_c – Temperature of solar panel, °C
G_{eff} — Effect solar radiation, MJ/m²
V_{Gt} – Thermal voltage of solar panel, V
V_{charge} — Battery charge voltage, V
$V_{discharge}$ — Battery discharge voltage, V
i — Battery current, A
E_0 — Battery constant voltage, V
K — Battery polarization constant, A/h
Q — Battery constant voltage, V
A — Exponential voltage, V
B — Exponential capacity, A/h
SEC — Specific energy consumption, kWh/m³
P_{sys} — RO working pressure, Pa
Y — RO permeate product water recovery
f_{os} — Membrane index
C_{feed} — Inlet water salinity, ppm
Q_p — Product flow rate, m³/h
C_{acap} — Annualized capital cost
CRF — Capital recovery factor
Y_{proj} — Lifetime of project, year
i — Interest rate, %
j — Nominal interest rate, %
f — Inflation rate, %
SFF — Sinking fund factor
C_{amain} — System maintenance cost, US$
NPV — Net present value
LCOP — Levelized cost of product, US$/m³
VOP — Volume of product, m³
OFC — Operating flow costs, US$
PC — Prime Cost, US$
AB — Annual benefit, US$
CC — Capital cost, US$
ρ — Fluid density, kg/m³
A_p — Pipe cross sectional area in RO system, m²
A_m — Active membrane surface area in RO system, m²
K_m — Overall mass transfer coefficient
V^f — Feed stream velocity, m/s
V_r — Sewage stream velocity, m/s
$\Delta\pi$ — Osmotic pressure difference across the surfaces of the membrane, Pa

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