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# Techno-economic feasibility of a solar-powered reverse osmosis desalination system integrated with lithium battery energy storage

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**ABSTRACT**

Today, energy and fresh water play a vital role in human life and the development of economics and also in industry. The energy density in water desalination process is remarkable, so using the renewable energy sources for this purpose can be interesting especially in the high potential renewable energy sources (solar energy) like Middle East. The simulation and feasibility study of solar water desalination system coupled with lithium battery energy storage is considered in the case study of Iran. For these purposes, a complete simulation of the considered system is done. Then, using simulation results, the economic study is carried out using tem economic method. Also, the parametric study is considered to find out the effect of climate change, temperature, solar panel type, size of system and the salinity of inlet water on the economic feasibility. Results show that the suggested system is economically feasible in the considered place (period of return is under 5 years). The minimum cost of market for desalinated water which causes the considered system economic is 0.045 US$/L in (Tehran and Jask), 0.04 US$/L for Semnan, 0.065 US$/L in Rasht and 0.035 US$/L in Yazd.

*Keywords:* Annualized cost of system; Solar radiation modeling; Solar water desalination; Lithium battery energy storage; Reverse osmosis

## 1. Introduction

The lack of fresh water is an increasing international problem that challenges many countries especially in Middle East. These countries such as Iran, Iraq and Saudi Arabia which are located in the desert area, witness a rapidly increasing population and industrial growth depending mainly on the water desalination as the main source of fresh water. The countries with water production per capita of less than 1,000 $m^3$/year are considered to be water-poor countries [1]. In addition to the high cost and energy consumption of the seawater desalination process, the transportation of the fresh water to the highly populated region in the central areas of these countries and to the small cities and villages over large distances across these arid countries adds to the cost considerably [2,3]. So, distributed water desalination especially relied on the renewable energy sources are a suitable way to provide drinking water. The objective of this paper is based on these concepts:

- Water leakage specially is central parts of the country
- People should pay extra money to purchase high quality drinking water
- Fuel price is increasing during the last 8 years and using thermal method is not economic in this condition
- The pollution which is generated from fossil fuel combustion are reached to the hazard level and the other energy sources with low pollution are needed.

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- The government policy during the last 5 years is based on the renewable energy development especially in rural and deprived area.

So, the authors have decided to study the desalination method based on the renewable energy sources and its technical and economic aspects. The application of renewable energy for freshwater generation had been considered by many researches during the last 10 years [4–11]. Table 1 shows a summary of these articles.

Considering the presented literature, it is obtained that:

- Renewable energy usage (especially solar PV) in desalination is recommended in remote area.
- Most of these studies are based on the simulation and software optimization and economic analyses are not considered perfectly.

So, in this paper, the simulation and feasibility study of solar water desalination system coupled with lithium battery

Table 1
Summary of articles which worked on the application of renewable energy on the fresh water production

| Authors | Article name (year) [Ref] |
|---|---|
| Miranda and Infield | A wind-powered seawater reverse-osmosis system without Batteries (2002) [12] |
| | Main content |
| • Development of small-scale stand-alone desalination systems in islands and in isolated inland areas is considered.<br>• Suggested system is 2.2 kW wind turbine generator powering a variable-flow reverse osmosis (RO) desalination unit.<br>• Operation at variable-flow allows the uncertainty and variability of the wind to be accommodated without need of energy storage. | |
| Al-Alawia et al. | Predictive control of an integrated PV-diesel water and power supply system using an artificial neural network (2007) [13] |
| • This paper discusses the development of a predictive artificial neural network (ANN)-based prototype controller for the optimum operation of an integrated hybrid renewable energy-based water and power supply system (IRWPSS).<br>• Integrated system consists of photovoltaic modules, diesel generator, battery bank for energy storage and a reverse osmosis desalination unit. The electrical load consists of typical households and the desalination plant.<br>• Key objectives are to reduce fuel dependency, engine wear and tear due to incomplete combustion and cut down on greenhouse gas emissions. | |
| Charcosset | A review of membrane processes and renewable energies for desalination (2009) [14] |
| • The idea of using renewable energy sources is fundamentally attractive and many studies have been done in this area. So, a review had been done by the author.<br>• This article provides a state-of-the art review on membrane processes associated with renewable energies for seawater and brackish water desalination.<br>• This article presents the main results in this field including principles, plant design and implementation, mathematical models and economic feasibility. | |
| Esfahani and Yoo | An optimization algorithm-based pinch analysis and GA for an off-grid battery less photovoltaic-powered reverse osmosis desalination system (2016) [15] |
| • Freshwater pinch analysis (FWaPA) as an extended pinch analysis technique has been proposed for retrofitting the off-grid batteryless photovoltaic-powered reverse osmosis system (PVS-RO) with a water storage tank to minimize the required outsourced freshwater.<br>• A multi-objective optimization algorithm by combining FWaPA numerical tool and genetic algorithm (FWaPAGA) minimizes three objective functions. | |
| Alkaisi et al. | A review of the water desalination systems integrated with renewable energy (2017) [16] |
| • Integration of the renewable energy into water desalination systems are considered in this study.<br>• Results of this study show that the economic performance evaluation of the renewable energy desalination systems and its comparison with conventional systems is not conclusive due to many varying factors related to the level of technology, the source of energy availability and the government subsidy.<br>• It also shows that the small renewable energy desalination plants have a high capital cost, low efficiency and productivity which make renewable energy desalination systems uncompetitive with the conventional ones.<br>• However, the selection of the small renewable energy desalination plants for the remote arid areas with small water demands is viable due to the elimination of the high cost of the water transportation and the connection to the electricity grid. | |

energy storage is considered in the case study of Iran. For this purposes, a complete simulation of the whole system is performed. The main parts of system simulation are solar radiation, photovoltaic solar panel, lithium battery and reverse osmosis desalination unit. Then using simulation results, the economic analyses are performed using annualized cost of system (ASC) economic method. Also, the parametric study is considered to find out the effect of climate change, temperature variation, solar panel type, size of system and the salinity of inlet water on the economic feasibility. It should be noted that all the calculations are done for five different cities in Iran (Tehran, Jask, Yazd, Semnan and Rasht) (shown in Fig. 1). Also, the solar radiation map of the country is given in Fig. 2.

## 2. System description

The main system which is considered in this article consists of a 1.4 $m^3/d$ brackish water reverse osmosis (BWRO) plant equipped with two membrane modules of the same capacity coupled with four photovoltaic (PV) panels. The water recovery efficiency of the considered RO system for brackish water is assumed to be 50% of the raw inlet water. The solar panels are (SHARP 235 W, Japan). The considered energy storage system is 200 Ah lithium batteries with voltage of 24 V. Fig. 3 shows a photograph and schematic of the desalination system. These types of system can produce with three, four or more solar PV panel based on the electrical energy requirement.

## 3. System simulation

The simulation of main parts of the system is presented in this section. Solar radiation, photovoltaic solar panel, lithium battery and reverse osmosis desalination units are the main parts of the simulation.

### *3.1. Solar radiation*

The photovoltaic (PV) cell can directly convert the sunlight into DC power through the photoelectric phenomena. So, at the first, solar energy must be simulated and the outlet results are applied to PV mathematical modeling. In several studies, total solar energy which is received by a sloped plate is estimated by the following equations [17].

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

where

$$r_t = \frac{\pi}{24} (a + b \cos\omega) \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180} \cos\omega_s} \quad (2)$$

$$r_d = \frac{I_d}{H_d} = \frac{\pi}{24} \left( \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180} \cos\omega_s} \right) \quad (3)$$


Fig. 1. Location of considered cities in the map country.

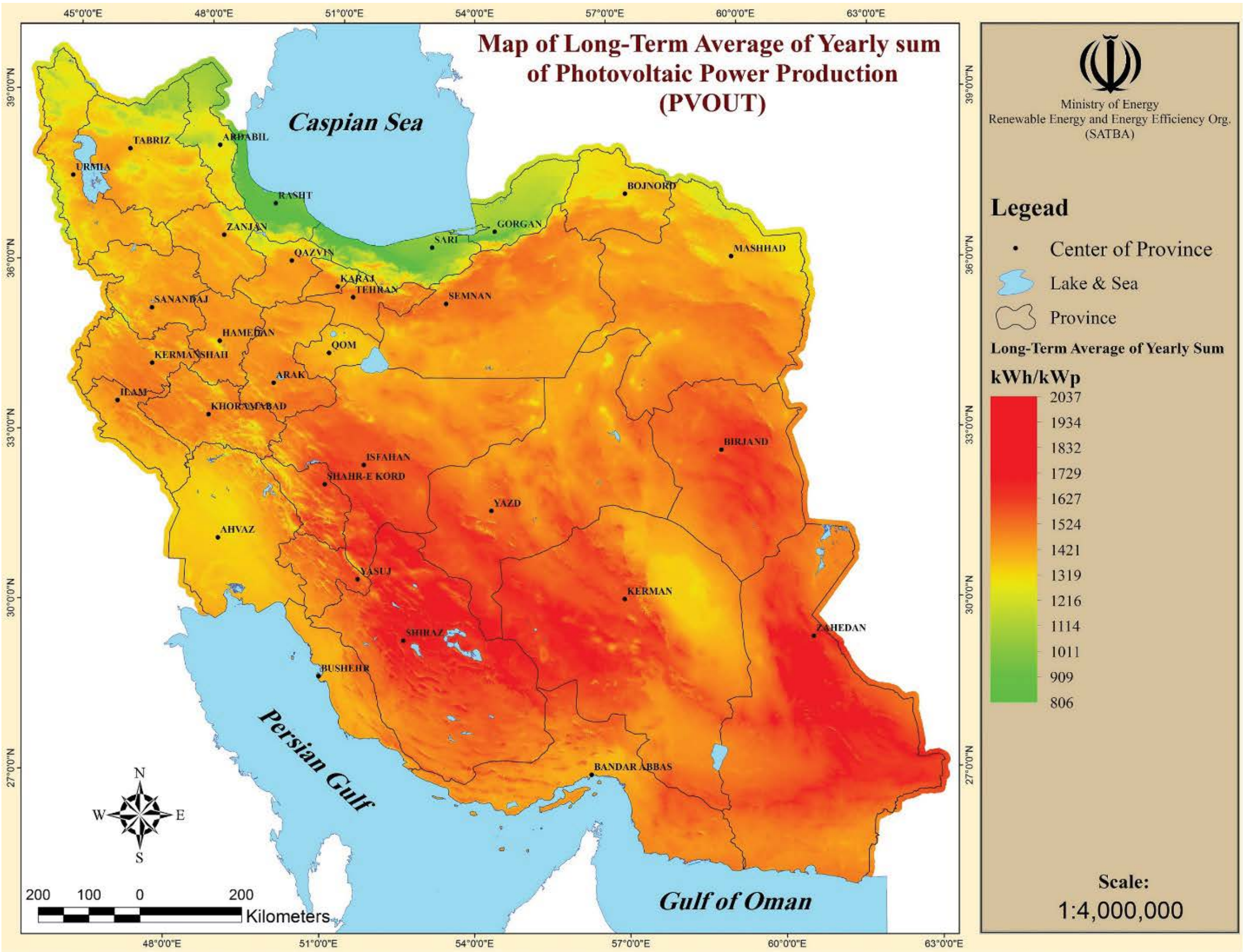


Fig. 2. Solar radiation map of Iran.

and

$$a = 0.409 + 0.5016\sin\left(\omega_s - 60\right) \quad (4)$$

$$b = 0.6609 - 0.4767\sin\left(\omega_s - 60\right) \quad (5)$$

where $\omega$, $\omega_s$ and $\rho_g$ are hourly angle, sunset hourly angle and reflection factor, respectively.

### 3.2. Photovoltaic solar panel

The operating voltage and current of PV determine the power output of the PV array which is depending on the light intensity falling on the PV module, the ambient temperature and the manufacturer characteristic of PV module.

The formulas for calculating the optimum operating point current and voltage under arbitrary conditions have the following forms [18]:

$$I_{SC}\left(G\right) = \frac{I^*_{SC}}{G^*}G_{eff} + \left(T_C - T^*_C\right)\mu_{I_{sc}} \quad (6)$$

$$V_{OC_{PV}}\left(T_C\right) = V^*_{OC_{PV}} + \left(T_C - T^*_C\right)\frac{dV_{OC_{PV}}}{dT_C} + V_t \ln\left(\frac{G_{eff}}{G^*}\right) = V^*_{OC_{PV}} + \left(T_C - T^*_C\right)\mu_{V_{OC}} \quad (7)$$

where $I_{SC}$, $V_{OC}$, $T_C$ and $G_{eff}$ are short circuit current, open circuit voltage and effect solar radiation, respectively. The technical data of SHARP 235 (Japan) that have been used in the PV simulation are presented in Table 2.

### 3.3. Lithium battery model

The lithium-ion battery is an ideal choice for a wide variety of applications due to its high energy, power density and operating voltage. Lithium ion batteries are used as a primary and a secondary power source in different applications. The usage of the lithium battery as secondary power sources is considered in this study. Lithium ion batteries gain more and more importance due to their higher specific capacity, longer life and lower self-discharging compared with conventional batteries such as lead acid. These properties are based on the use of lithium and intercalation materials from which

Table 2
Technical data of solar array Sharp 235 ND-Q235F4 [19]

| Parameter | Magnitude | Parameter | Magnitude |
|---|---|---|---|
| Short-circuit current (A), $I_{SC}$ | 8.89 | Nominal output (W), $P_{mpp}$ | 235 |
| Open-circuit voltage (V), $V_{OC}$ | 37.4 | Voltage/temperature coefficient (V/°C), $\mu_{VOC}$ | –0.351 |
| Nominal current (A), $I_{mpp}$ | 8.05 | Current/temperature coefficient (A/°C), $\mu_{ISC}$ | 0.053 |
| Nominal voltage (V), $V_{mpp}$ | 29.2 | Number of series cell, $N_S$ | 60 |

the electrodes are formed. The general model for charge and discharge of lithium battery is presented as:

$$V_{\text{charge}} = E_0 - K\frac{Q}{Q-\text{it}}\times i - K\frac{Q}{Q-\text{it}} + A.\exp\left(-B.\text{it}\right) \quad (8)$$

$$V_{\text{discharge}} = E_0 - K\frac{Q}{0.1Q+\text{it}}\times i - K\frac{Q}{Q-\text{it}} + A.\exp\left(-B.it\right) \quad (9)$$

where $i$ is the battery current (A), $E_0$ is the constant voltage (V), $K$ is the polarization constant (Ah$^{-1}$) or polarization resistance (Ω), $Q$ is the maximum battery capacity (Ah), $A$ is the exponential voltage (V) and $B$ is the exponential capacity (Ah$^{-1}$) [20,21].

### *3.4. Reverse osmosis desalination unit*

A simple reverse osmosis desalination modeling is developed in this section [22]. The considered configuration is presented in Fig. 4.

The RO system is illustrated in Fig. 4 where $P_f$, $Q_f$ and $X_f$ are the feed high pressure, flow rate and salt concentration, respectively. The high pressure forces the water to pass through the membrane to the permeate side. The pressure at the brine side is denoted by $P_b$. Similarly, the brine flow rate and concentration are denoted by $Q_b$ and $X_b$, respectively. The permeate water flow rate is $Q_p$ and its concentration is presented as $X_p$.

Osmotic pressure is one of the important parameter in RO modeling and it is a function of temperature and salt concentration in the feed water [23]. To have positive permeate flow, the operating pressure needs to be greater than the osmotic pressure. Other relations that are used in reverse osmosis are collected in Table 3.

In the simulation of solar desalination water system, the following assumptions have been considered:

- Feed water has salinity about 2,000–5,000 ppm and its temperature is assumed to be 25°C.
- Feed water has no contaminations such as microorganism, heavy metals, grease, etc.
- Energy efficiency of charge controller and inverter are assumed to be 99% and 94%, respectively.
- Turbidity of feed water is in the allowable range of RO system.
- Disinfection process of RO product water was performed by UV filter.

It should be noted that the water recovery is assumed to be 50% in all the simulations of BWRO units. It means that half of inlet water is rejected into the ambient with the higher magnitude of salinity. To prevent the environmental effect of this rejection, two methods are considered. In dry cities such as Semnan, Tehran and Yazd, the surface evaporation is suggested for the brine and for the humid areas such as Rasht and Jask, the absorbing well is suggested.

## 4. Economic evaluation

The economic evaluation of the introduced configuration is considered in this section. According to the concept of ASC, the economic approach is developed in this study. ACS is composed of annualized capital cost $C_{acap}$, annualized replacement cost $C_{arep}$, annualized maintenance cost $C_{amain}$ and annualized operating cost $C_{aope}$ [26–29]. The project lifetime is assumed to be 10 years. ACS can be expressed for presented configuration according to Eq. (15).

ACS = $C_{acap}$ (solar PV panel + reverse osmosis membrane and pressure vessel + (pumping system) high pressure pump and inlet feed pump + lithium battery + trailer + other instruments) + $C_{arep}$ (solar PV panel + reverse osmosis membrane and pressure vessel + (pumping system) high pressure pump and inlet feed pump + lithium battery + trailer + other instruments) + $C_{amain}$ (solar PV panel + reverse osmosis membrane and pressure vessel + (pumping system) high pressure pump and inlet feed pump + lithium battery + trailer + other instruments) (15)

The relations used in the economic analyses are presented in Table 4.

## 5. Results and discussion

### *5.1. Technical results*

#### *5.1.1. Monthly energy production, storage and freshwater production in selected cities*

As it is mentioned before, all the calculations are performed for five different cities in different climate areas. Fig. 1 shows the location of the considered cities in the country map. For these case studies, the outlet results are presented as follows. All the calculations are performed using MATLAB commercial software. Fig. 5 shows the energy production from the solar system (four solar panel with the capacity of 235 W) for a period of 12 months and in the selected cities.

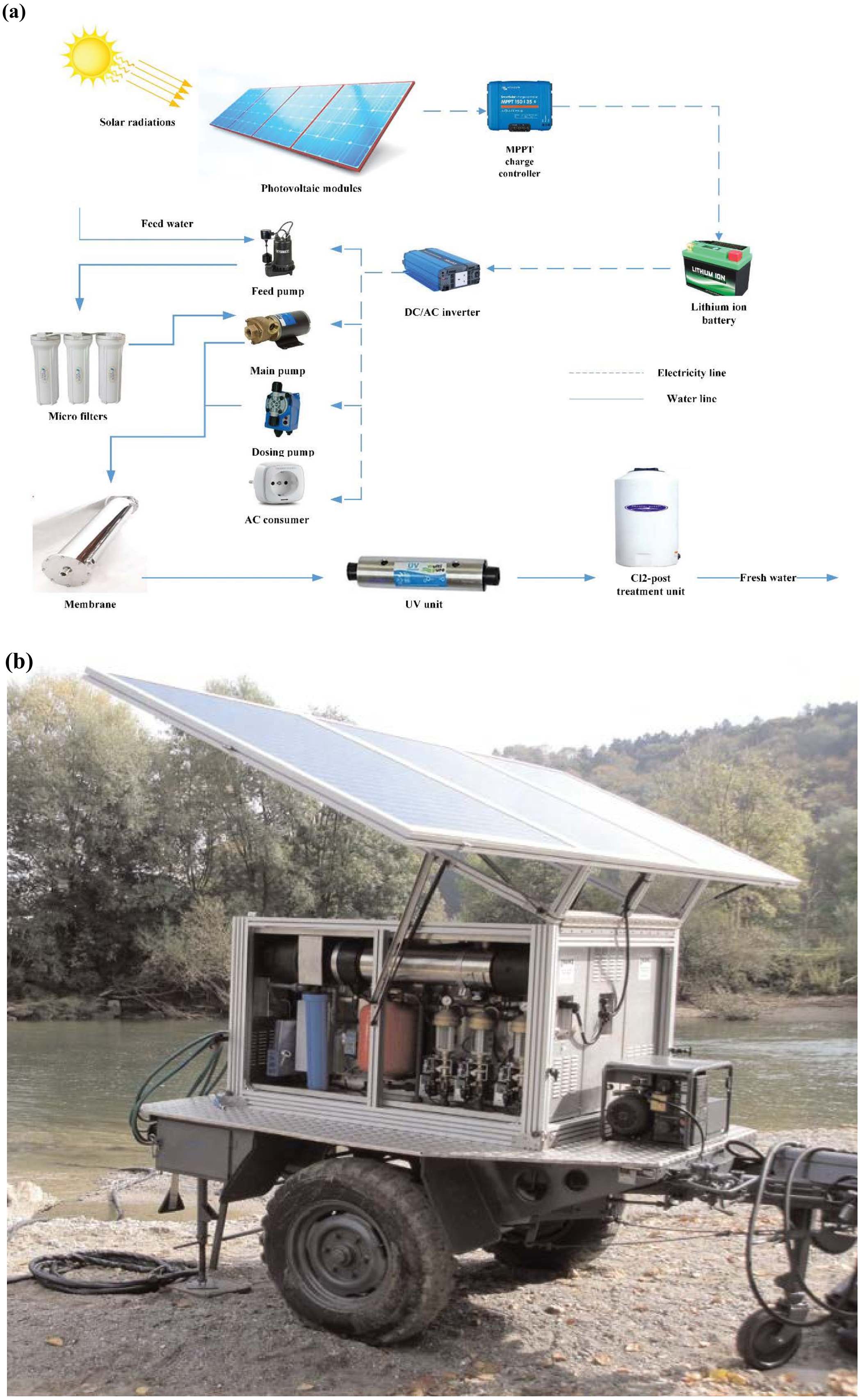


Fig. 3. (a,b) Photograph and schematic of the main system.

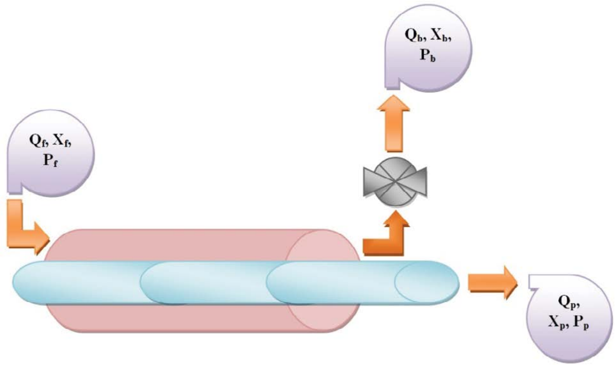


Fig. 4. Scheme of reverse osmosis desalination unit.

For better comparison, Fig. 6 shows the cumulative monthly energy production in five selected cities.

Results show that the city (Yazd) has the best energy production and the city (Rasht) has the worst one. It also shows that Tehran and Semnan are similar in solar energy production. According to these results, Fig. 7 shows the amount of energy storage in the lithium battery pack during the different month and in five selected cities. More investigation shows that the produced energy is sufficient to complete the charge of the lithium battery pack during most of the time of the year in all cities except that Rasht. The specific energy consumption (SEC) is the most important parameter in reverse osmosis desalination plant simulation. The results of SEC calculation in different nominal size of system are presented in Table 5. It should be noted that the inlet water salinity is assumed to be 2,000 ppm in this study. The efficiency of water pump is assumed to be 70% and other electrical consumption of the considered system is assumed to be 30% of main pump work.

Now, using the SEC of first designed system (with four solar PV panels) and the energy production in five selected cities. Fig. 8 shows the magnitude of desalinated water production in the month of the year.

#### 5.1.2. Daily energy production and consumption in selected cities

To investigate the energy production and consumption during a day, Fig. 9 shows the magnitude of energy production and consumption on 5th of July and in five selected cities. It is assumed that the reverse osmosis system is turned on at 10:00 AM and operates for 5 h.

Results show that the energy production from PV panels is not sufficient to support the 5 h operation of reverse osmosis system in Rasht. But in other cities, it is clear that the energy production covers the energy consumption by reverse osmosis desalination system.

### 5.2. Technical parametric study

#### 5.2.1. Effect of ambient temperature on the PV system energy production

Ambient temperature is one of the important parameters in the solar PV system. It means that the increment in ambient temperature causes decrement in energy production form solar PV panel. Fig. 10 shows the effect of average temperature increment (plus 10°) and decrement (minus 10°) on the desalinated water production in Yazd. Finally, economic analyses can show the effect of ambient temperature on the system feasibility.

#### 5.2.2. Effect of solar panel technology on the PV system energy production

The solar PV panel technology improved during the last 5 years and now the PV panel can produce the same energy in the smaller size and also with the lower weight. It should

Table 3
Relations that are used in reverse osmosis [24,25]

| Relation | Description | Eq. number |
|---|---|---|
| $\text{SEC} = \frac{\Delta P}{Y} = \frac{P_{\text{sys}}}{Y}$ | Specific energy consumption (SEC) defined as the electrical energy needed to produce a cubic meter of permeate ($P_{\text{sys}}$ and $Y$ are working pressure and water recovery) | (10) |
| $P_{\text{sys}} = \frac{\rho A_p}{A_m k_m}\left(V_f - V_r\right) + \Delta\pi$ | 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) | (11) |
| $Y = \frac{Q_p}{Q_f}$ | Permeate product water recovery for the RO process | (12) |
| $\Delta\pi = f_{\text{os}} C_{\text{feed}} \frac{\ln\left(\frac{1}{1-Y}\right)}{Y}$ | Osmotic pressure difference across the surfaces of the membrane ($f_{\text{os}}$ is an empirically obtained constant [$f_{\text{os}} = 78.7$] [24,25]) | (13) |
| $Q_p = \frac{E_{\text{PV}}}{\text{SEC}}$ | Product flow rate ($Q_p$) can be extracted by $E_{\text{PV}}$ (energy of photovoltaic) | (14) |

Table 4
Relations that are used in the economic analyses [26–32]

| Relation | Definition | Relation number |
|---|---|---|
| $C_{\text{acap}} = C_{\text{cap}} \times \text{CRF}\left(i\ \&\ Y_{\text{proj}}\right) = C_{\text{cap}} \times \frac{i \times (i+1)^{Y_{\text{proj}}}}{(i+1)^{Y_{\text{proj}}} - 1}$ | Annualized capital cost and capital recovery factor (CRF) is a ratio to calculate the present value of an annuity | (16) |
| $i = \frac{j - f}{1 + f}$ | Annual real interest rate ($i$) is related to the nominal interest rate ($j$) and the annual inflation rate ($f$) which the magnitude of these parameters are 9.25%, 18% and 8%, respectively, in May 2017 | (17) |
| $C_{\text{rep}} = C_{\text{cap}}\left(\text{In Base Year}\right) \times (i+1)^{Y_{\text{rep}}}$ | Future cost of each component | (18) |
| $C_{\text{arep}} = C_{\text{rep}} \times \text{SFF}\left(i\ \&\ Y_{\text{rep}}\right) = C_{rep} \times \frac{j}{(i+1)^{Y_{\text{rep}}} - 1}$ | SFF is the sinking fund factor which is a ratio to calculate the future value of series of equal annual cash flows (in this study the magnitude of replacement cost in neglected) | (19) |
| $C_{\text{amain}}$ | System maintenance cost is deemed to be constant every year (10% of capital cost) | (20) |
| $C_{\text{aope}}$ | Annual labor cost and insurance cost of the considered system are computed as an annualized operating cost (3,000 US$/person/year) and (0.02 of capital cost for insurance cost) | (21) |
| $\text{NPV} = \frac{\text{ACS}}{\text{CRF}\left(i\ \&\ Y_{\text{proj}}\right)} = \text{ACS} \times \frac{(i+1)^{Y_{\text{proj}}} - 1}{i \times (i+1)^{Y_{\text{proj}}}}$ | Net present value is the present value of installing and operating the system over its lifetime in the project | (22) |
| $\text{LCOP} = \frac{\text{ACS}}{\text{Annual Output Product of the System}}$ | Levelized cost of product is the average cost per unit (US$/L) of useful total product of the system | (23) |
| Capital costs (CC) | Total purchase cost + 0.15 (installation cost) | (24) |
| Operating flow costs (OFC) | which includes operating and maintenance costs, labor cost and insurance cost calculated for 1 year | (25) |
| Volume of product (VOP) | which is the volume of product in 1 year | (26) |
| $\text{PC} = \frac{\text{OFC}}{\text{VOP}}$ | Prime cost (PC) and it is equal to division of operating flow costs on volume of product | (27) |
| Cost of product (COP) | It is equal to value of product in the local market | (28) |
| $\text{SOPC} = (\text{VOP}) \times (\text{COP})$ | Summation of product cost (SOPC) and it is equal to multiplication of volume of product and cost of product | (29) |
| $\text{AB} = (\text{SOPC} - \text{OFC})$ | Annual benefit (AB) and it is equal to subtraction of operation flow costs from summation of product cost | (30) |
| Net annual benefit (NAB) | It is equal to subtraction of tax cost (10% of annual benefit) from annual benefit | (31) |
| $\text{ROR} = \frac{\text{NAB}}{\text{CC}}$ | It is equal to division of net annual benefit on capital costs | (32) |
| $\text{POR} = \frac{\text{CC}}{\text{NAB}}$ | It is equal to division of capital costs on net annual benefit | (33) |
| $\text{AV} = \text{COP} - \text{PC}$ | It is equal to subtraction of prime cost from cost of product | (34) |

(*continued*)

Table 4 Continued

| $C_{cap}$ (purchase cost of instrument) | | |
|---|---|---|
| $C_{Cap}$ (solar) = solar PV panel (local price in the country) | 1–5 kW (1,261 US$/kW)<br>5–20 kW (945 US$/kW)<br>20–100 kW (783 US$/kW)<br>100–1,000 kW (675 US$ per kW) | (35) |
| $C_{Cap}$ (RO) = reverse osmosis membrane and pressure vessel [30] | Membrane (1,666 L/h) (858 US$)<br>Pressure vessel (1,666 L/h) (500 US$)<br>Membrane (458 L/h) (236 US$)<br>Pressure vessel (458 L/h) (250 US$)<br>Membrane (133 L/h) (68 US$)<br>Pressure vessel (133 L/h) (100 US$)<br>Membrane (58 L/h) (30 US$)<br>Pressure vessel (58 L/h) (50 US$) | (36) |
| $C_{Cap}$ (HPP) = pumping system (high pressure pump) [31] | Inlet mass flow rate (over than 450 $m^3/h$)<br>393,000 + 10,710 (operating pressure)<br>Inlet mass flow rate ($200 < x < 450$ $m^3/h$)<br>81 ((Inlet mass flow rate)(operating pressure))$^{0.96}$<br>Inlet mass flow rate (less than 200 $m^3/h$)<br>52 (inlet mass flow rate)(operating pressure) | (37) |
| $C_{Cap}$ (FP) = pumping system (inlet feed pump) [32] | 705.48(power of pump)$^{0.71}$<br>(1 + (0.2/(1-pump efficiency))) | (38) |
| $C_{Cap}$ (T) = trailer (local price in the country) | With the capacity 500 L/d (2,970 US$)<br>With the capacity 1,000 L/d (3,864 US$)<br>With the capacity 10,000 L/d (11,594 US$)<br>With the capacity 100,000 L/d (34,783 US$) | (39) |
| $C_{Cap}$ (B) = battery (local price in the country) | Number of cell = (voltage/3)(capacity in unit of A h/10)<br>Total price (US$) = 9.45 (number of cells) (1.3) | (40) |
| Other price of system | 1.3 (total capital cost) | (41) |

be noted that the price of PV panel with this technology increases per W in comparison with the previous technology. Fig. 11 shows the magnitude of water production (in solar water desalination system) from new technology PV panel, the old one and an Iranian-made PV panels and in the case study of Yazd.

#### *5.2.3. Effect of inlet water salinity on the specific energy consumption and amount of freshwater production*

The salinity of inlet water is one of the important parameters which is studied in this section. Fig. 12 shows the effect of inlet water salinity on the SEC and also on the freshwater production in the case of Yazd.

### *5.3. Economic analyses results*

#### *5.3.1. General economic results*

General economic assumptions and results are presented as Table 6. All the economic evaluations are performed for the Yazd (a city in the central part of Iran).

General results show that the suggested system is economically feasible in the considered place (period of return is under 5 years). It should be noted that the price of drinking water in some parts of the country is about 0.04 US$/L and the price of drinking water bottle with the high quality standard is about 0.27 US$/L which is equal to the price of gasoline/L [33].

#### *5.3.2. Economic evaluation of the considered system in different cities*

Five cities with the specific climate are selected in this section. Tehran (capital), Rasht (north of the country), Semnan and Yazd (central part of the country in the desert area and the Jask (south of the country) which the latitude and longitude of them are presented in Table 7.

Fig. 13 shows the variation of period of return during different cost of market of desalinated water in selected cities.

Results show that the considered system is economically feasible in the cost of market of 0.04 US$/L desalinated water in Tehran, Jask and Semnan (the period of return is under 5 years), 0.06 US$/L desalinated water in Rasht and 0.035 US$/L desalinated water in Yazd and also for the cost of market which was more than these price in the selected cities.

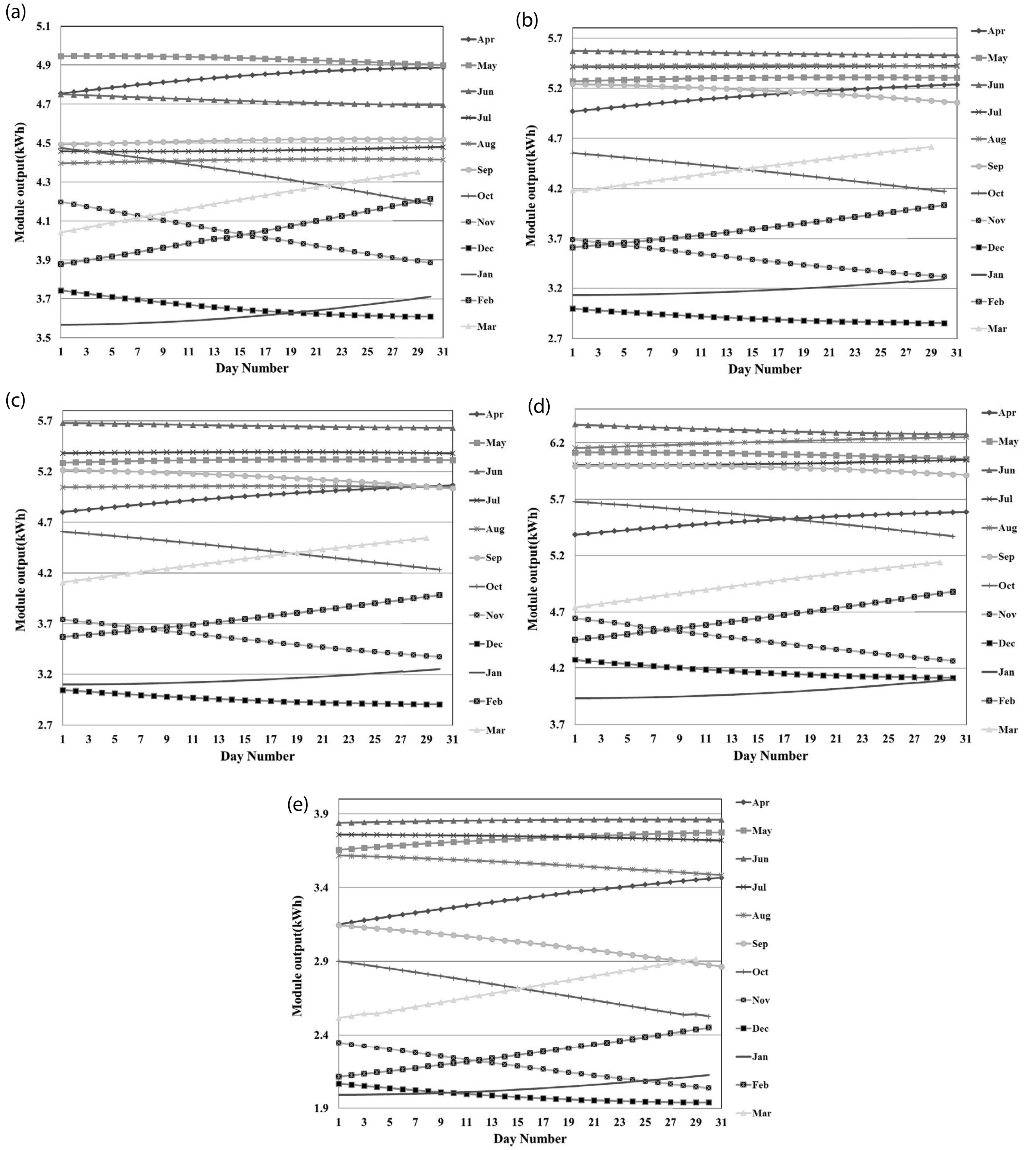


Fig. 5. Energy production from the solar system (four solar PV panels with the capacity of 235 W). City names: (a) Jask, (b) Semnan, (c) Tehran, (d) Yazd, and (e) Rasht.

*5.3.3. Economic evaluation of the considered system in different sizes*

For this purpose, five different sizes are selected in this section (500; 1,000; 10,000 and 100,000 L/d are chosen as considered capacity of suggested RO system). The required energy of considered RO systems is supplied by PV solar panels. Table 8 shows the general data for the selected system. It is assumed that the configuration of selected system is fixed and the location of installation is changed. So, the value

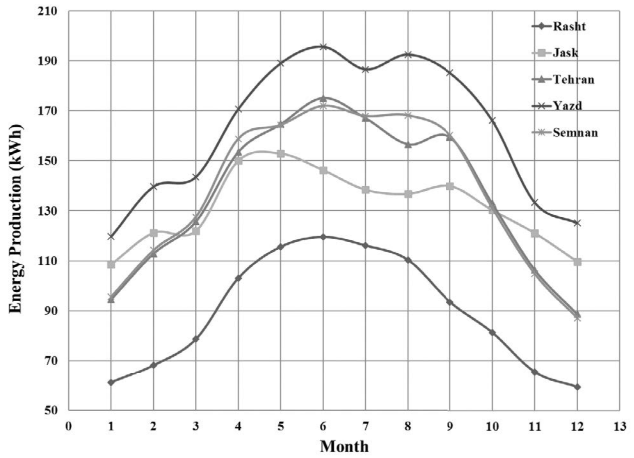


Fig. 6. Cumulative monthly energy production in five selected cities.

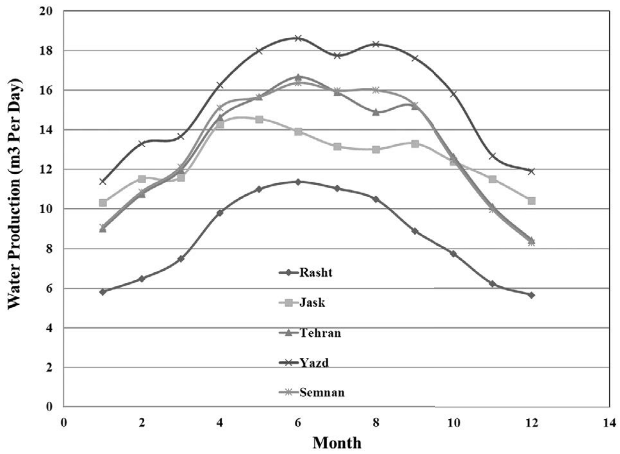


Fig. 8. Desalinated water production monthly in five cities of Iran.

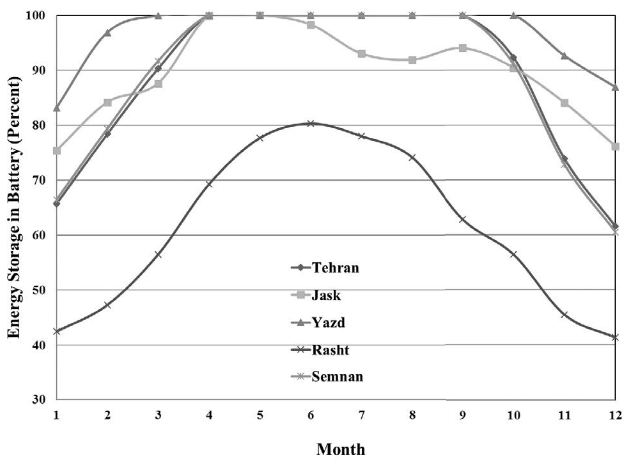


Fig. 7. Status of energy storage in lithium battery in different cities.

of generated power and also desalinated water is changed. Fig. 14 shows the variation of period of return through different size and in selected cities. It should be noted that the selected sizes of the system can produce the desalinated water with the nominal capacity in the cities with the lowest inlet solar energy and in 5 h.

Results show that the feasibility of considered systems are increased during the size increment. This increment is remarkable in the cities with the lower solar radiation same as Rasht. It is also showed that the suggested systems are economically feasible in size of 10,000 and 100,000 L/d. But in size of 1,000 L/d, the suggested system is economically feasible (period of return under 5 years) in the cost of product in the market of 0.03, 0.045, 0.03 and 0.035 US$/L in Tehran, Rasht, Semnan and Jask, respectively. It also shows in the size of 500 L/d, the suggested system is economically feasible (period of return under 5 years) in the cost of product in the market of 0.035, 0.045, 0.065, 0.04 and 0.045 US$/L in Yazd, Tehran, Rasht, Semnan and Jask, respectively.

#### *5.3.4. Effect of different solar panel technology in the economic analyses*

To do this, three different type of solar PV panel are selected. A mono crystal type which has an ordinary technology (Sharp 235 W, Japan), an Iranian solar panel (Pak Atiye) and new technology solar panel (LG 320 W). The main characteristics of considered PV panels are presented in Table 9.

Size of the systems is assumed to be 500 L/d and all the calculations are done for Yazd. The total capital cost of the system with the solar PV (Sharp 235 (Japan), PA 250 and for LG 320) are 10,672; 10,497 and 11,114, respectively. Economic results show that the capital cost of system in Iranian-made solar PV panel is less than the others. Fig. 15 shows the variation of period of return during the cost of market in the three suggested solar PV panels. Results show that although the capital cost of system is the highest in the new technologies, the results indicated that the extra power generation can make the system more feasible. So, more desalinated water can be achieved using the new

Table 5
Design parameters in different nominal size of system

| Nominal size (L/d) | Δπ (Pa) | $P_{sys}$ (Pa) | SEC (kWh/m$^3$) | Pump power (kW) | No. membranes |
|---|---|---|---|---|---|
| 500 | 218,202 | 1,411,406 | 1.12 | 0.160 | 2 |
| 1,000 | 218,202 | 1,319,621 | 1.05 | 0.299 | 2 |
| 10,000 | 218,202 | 1,809,140 | 1.44 | 4.102 | 5 |
| 100,000 | 218,202 | 1,508,152 | 1.20 | 34.198 | 12 |

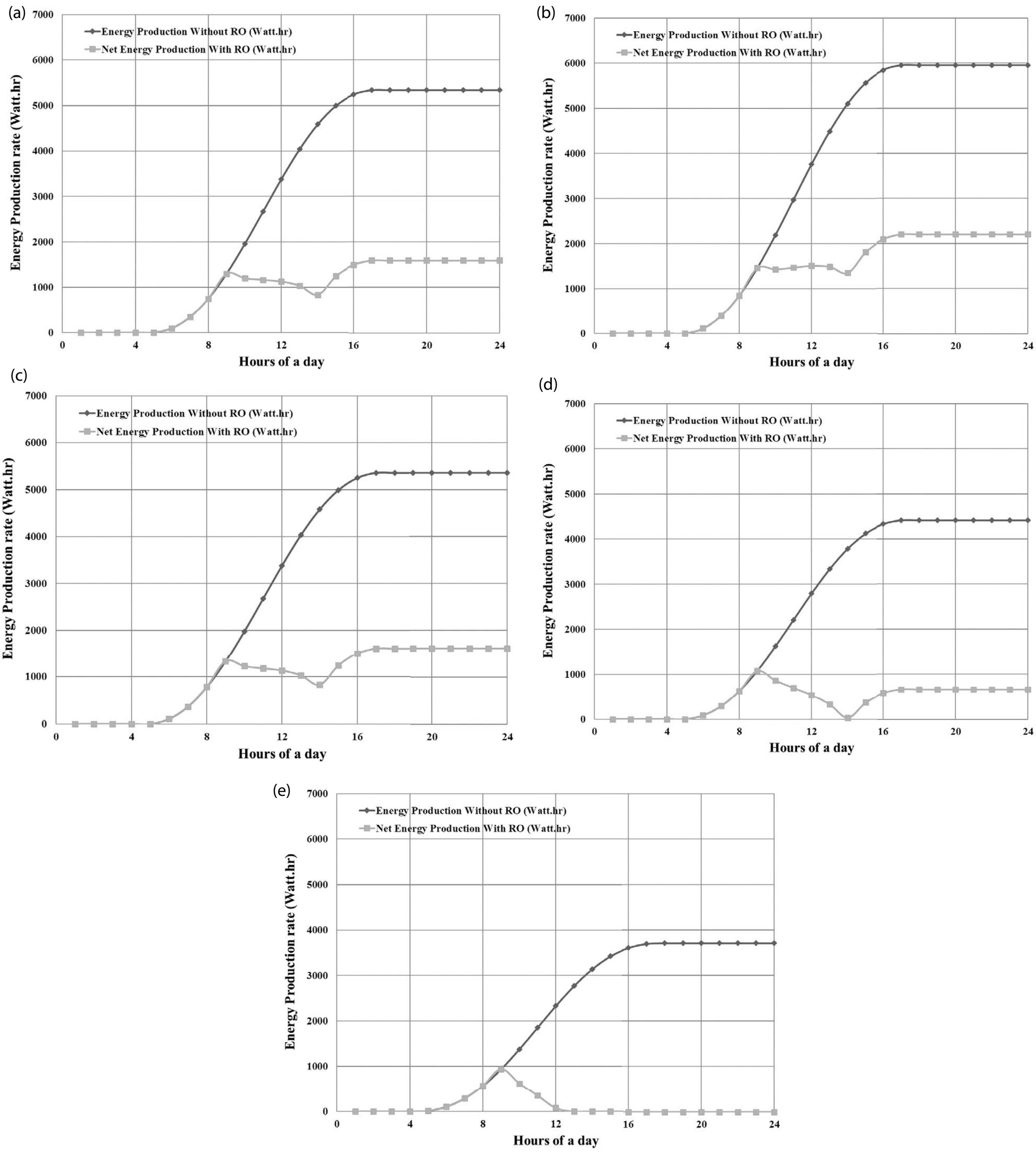


Fig. 9. Magnitude of energy production and consumption on the 5th of July (a) city of Tehran, (b) city of Yazd, (c) city of Semnan, (d) city of Jask, and (e) city of Rasht.

PV technology. The magnitude of desalinated water which is produced by the considered PV technologies (Sharp 235 (Japan), PA 250 and for LG 320) are 185,271; 165,032 and 242,533 L/d, respectively.

*5.3.5. Effect of ambient temperature in the economic analyses*

As mentioned before, the PV solar panel efficiency decreases during the ambient temperature increment. To investigate the effect of this variation on the economic aspect of the system, it is assumed that for the same condition and in one city (Yazd), the average ambient temperature increases and decreases 10°C and the economic evaluations are done. Fig. 16 shows the results of this examination. Results show that this variation in the lower cost of product is more than the higher one. It means that if the cost of product is higher than 0.035 US$/L, the temperature effect is negligible.

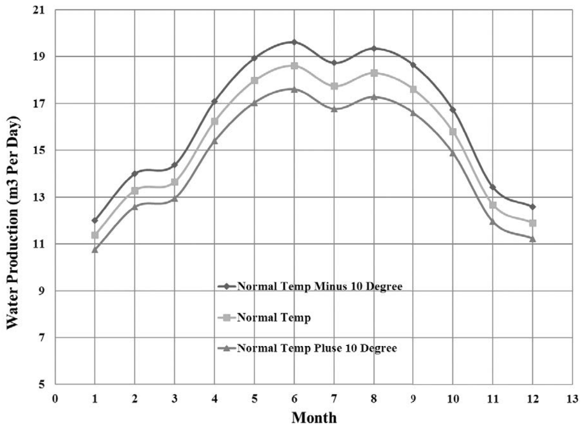


Fig. 10. Effect of average temperature increment (plus 10°) and decrement (minus 10°) on the desalinated water production in Yazd.

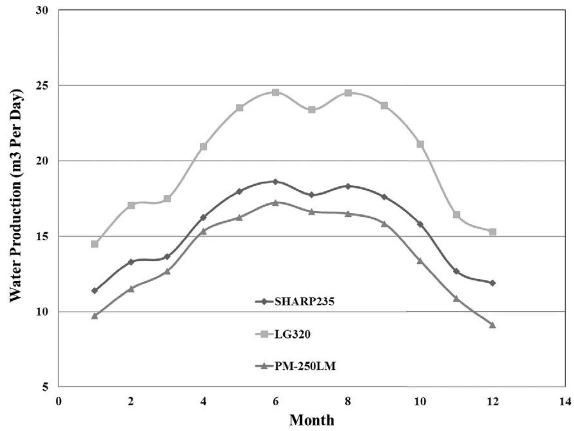


Fig. 11. Solar panel type effect on the amount of desalinated water production in Yazd.

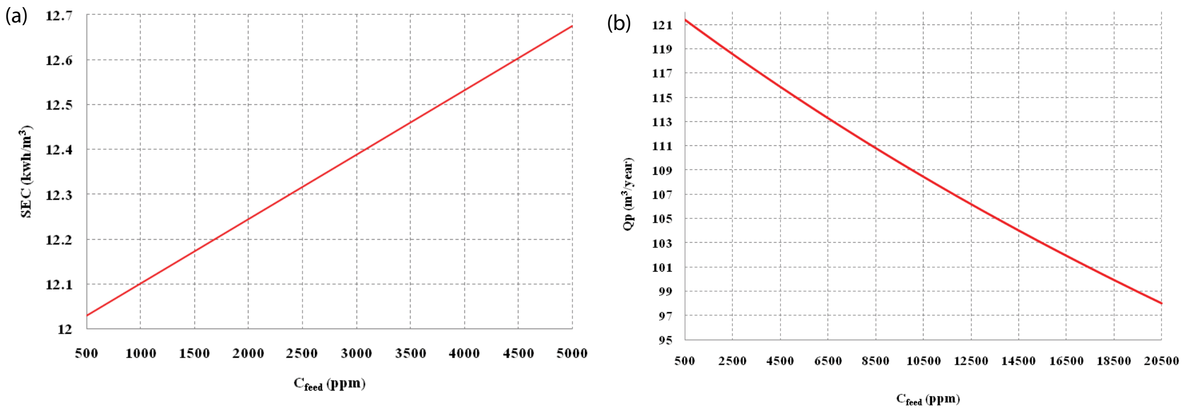


Fig. 12. (a) Effect of inlet water salinity on the specific energy consumption and (b) also on the freshwater production in the case of Yazd.

Table 6
General economic assumptions and results

| Nominal capacity of the system (L/d) | Number of solar panels | Capacity of lithium battery (A h) | Total capital cost (US$) |
|---|---|---|---|
| 500 | 4 (Sharp 235 W) | 200 (24 V) | 10,672 |
| Total installation cost (US$) | Total insurance cost (US$/year) | Cost of product (US$/L) | Installation cost (% of total cost) |
| 1,600 | 213.45 | 0.04 | 15 |
| Insurance cost (% of total cost) | Number of labor | Maintenance cost (% of total cost) | Cost of labor (US$/person/month) |
| 2 | 1 | 0.1/year | 250 |
| Volume of product (L/year water) | Prime cost of product (US$/L) | Period of return (year) | Rate of return (%) |
| 185,271 | 0.01734 | 3.24 | 0.307 |
| Annual benefit (US$) | Net annual benefit (US$) | NPV (US$) | ACS (US$) |
| 4,197 | 3,777 | 37,833 | 5,962 |
| Annual tax (US$) | LCOP (US$/L) | Additive value (US$/L) | Summation of product cost (US$/year) |
| 419.7 | 0.0321 | 0.0226 | 7,410 |

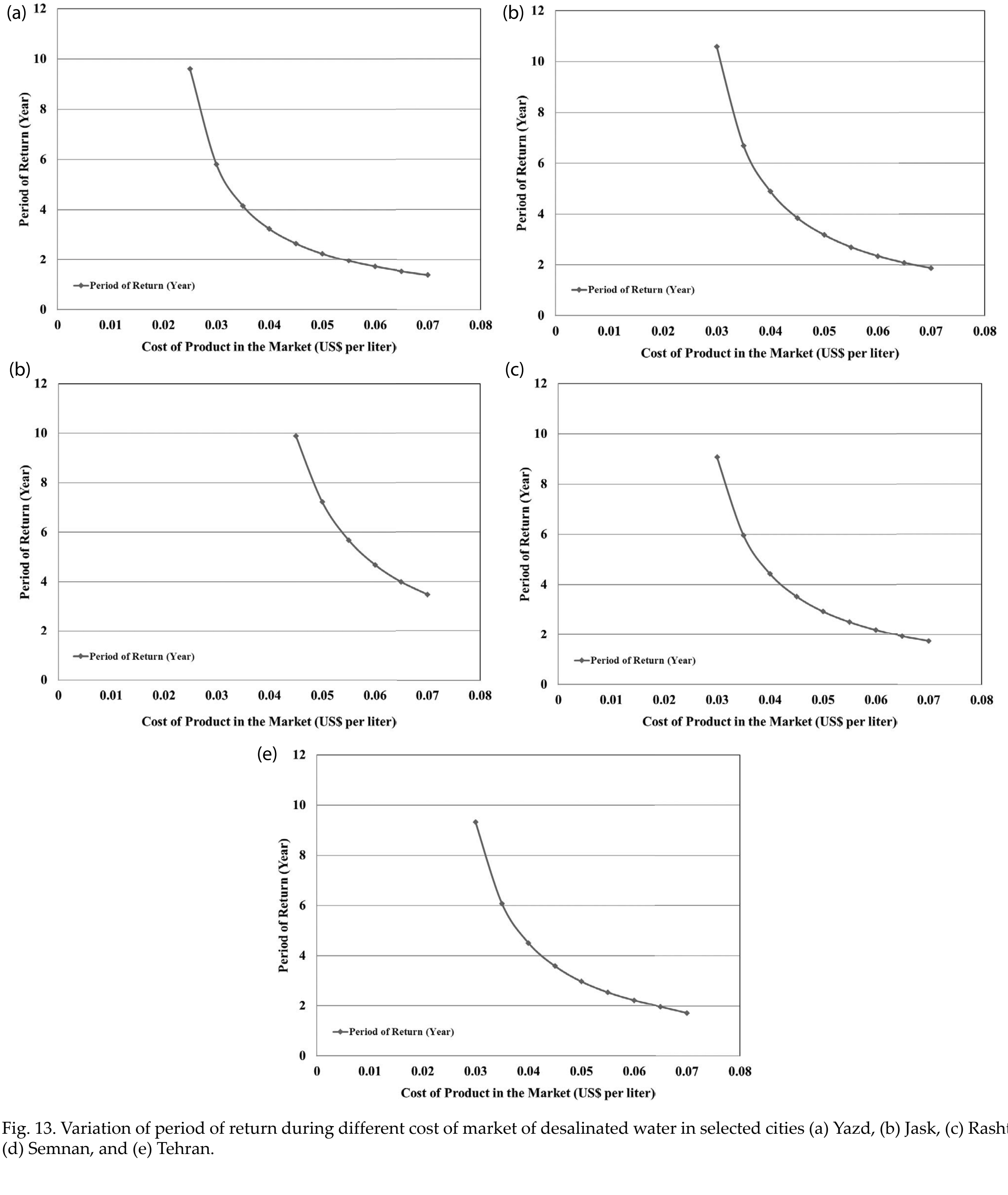


Fig. 13. Variation of period of return during different cost of market of desalinated water in selected cities (a) Yazd, (b) Jask, (c) Rasht, (d) Semnan, and (e) Tehran.

*5.3.6. Effect of inlet water salinity in the economic analyses*

The increment of the amount of inlet water salinity causes the decrement in the desalinated water production and obviously on the operating and maintenance cost of the system. To evaluate the effect of inlet water salinity, the value of inlet water salinity is changed from 500 into 20000 ppm and the period of return is calculated. The calculations are done for the city (Yazd) and for the capacity of 500 L/d RO system. Fig. 17 shows the results of this evaluation. Results show that the effect of inlet water salinity on the period of return in not linear and the variations are more obvious in the higher inlet water salinity.

Table 7
Latitude and longitude of the selected cities [34]

| City | Latitude | Longitude |
|---|---|---|
| Rasht | 37.33 | 49.96 |
| Semnan | 36 | 53.38 |
| Jask | 25.63 | 57.77 |
| Tehran | 35.73 | 51.06 |
| Yazd | 32 | 54.6 |

## 6. Conclusion

In this article, the simulation and feasibility study of solar water desalination system coupled with lithium battery energy storage is considered in the case study of Iran. For these purposes, a complete simulation of the considered system is done. In this part, results show that the city Yazd has the best energy production and the city Rasht has the worst one. It also shows that, the energy production from PV panels is not sufficient to support the 5 h operation of reverse osmosis system in Rasht. But in other cities, it is clear that the energy production covers the energy consumption by reverse osmosis desalination system. Then, using simulation results the economic study is carried out using ASC economic method. General results of economic analyses show that the suggested system is economically feasible in the considered cities (period of return is under 5 years). Finally, the parametric study is considered to find out the effect of climate change, ambient temperature, solar panel technology, size of system and the salinity of inlet water on the technical and economic feasibility. Size of the considered system is investigated as a part of technical and economic parametric study. For this purpose, five different sizes are selected in this section. 500; 1,000; 10,000 and 100,000 L/d are chosen as considered capacity of suggested plant. Results show that the feasibility of considered system is increased during the size increment. This increment is more obvious in the cities with the lower solar radiation same as Rasht. It is also showed that the suggested system is economically feasible in size of 10,000 and 100,000 L/d. But in size of 1,000 L/d, the suggested system is economically feasible (period of return under 5 years) in size cost of product in the market of 0.03, 0.045, 0.03 and 0.035 US$/L in Tehran, Rasht, Semnan and Jask, respectively. It also shows in the size of 500 L/d, the suggested system is economically feasible (period of return under 5 years) in size cost of product in the market of 0.035, 0.045, 0.065, 0.04 and 0.045 US$/L in Yazd, Tehran, Rasht, Semnan and Jask, respectively. In the economic parametric study, the PV panel type is changed and the economic parameters are calculated. Results show that although the capital cost of system is the highest in the new technologies but the results indicated that the extra power generation can make the system more feasible. The magnitude of desalinated water through using the considered PV technologies (Sharp 235 (Japan), PA 250 and for LG 320) are 185,271, 165,032 and 242,533 L/d, respectively. The effect of ambient temperature in the economic analyses is investigated is this study too. To calculate the effect of this variation on the system economic, it is assumed that for the same condition and in one city (Yazd), the average ambient temperature increases and decreases 10°C and the economic evaluation is done. Results show that temperature variations

Table 8
General data for the selected system sizes

| Size of system (L/d) | Number of solar panel (Sharp 235 W) | Type of membrane | Number of membranes |
|---|---|---|---|
| 500 | 4 | XLE-2521 | 2 |
| 1,000 | 13 | XLE-2540 | 2 |
| 10,000 | 142 | LP-4040 | 5 |
| 100,000 | 946 | BW30-400 | 12 |
| Size of system (L/d) | Power consumption (kW) | Latium battery capacity (A h) | Total capital cost (US$) |
| 500 | 0.160 | 142 | 8,826.31 |
| 1,000 | 0.299 | 461 | 19,832.68 |
| 10,000 | 4.102 | 5,036 | 128,726.39 |
| 100,000 | 34.198 | 33,545 | 754,391.05 |

Table 9
Main characteristics of considered PV panels

| PV panel type | Nominal power in STC (W) | Weight (kg) | Dimension cm × cm × cm | $V_{oc}$ (V) | $I_{sc}$ (A) | NOCT (°C) |
|---|---|---|---|---|---|---|
| Sharp 235 | 235 | 19 | 164 × 95.8 × 4.6 | 37.4 | 8.89 | 47.5 |
| PA 250 | 250 | 20 | 164 × 99.2 × 4.5 | 37.5 | 8.88 | 47 |
| LG 320 | 320 | 17 | 164 × 100 × 4 | 40.9 | 10.05 | 46 |

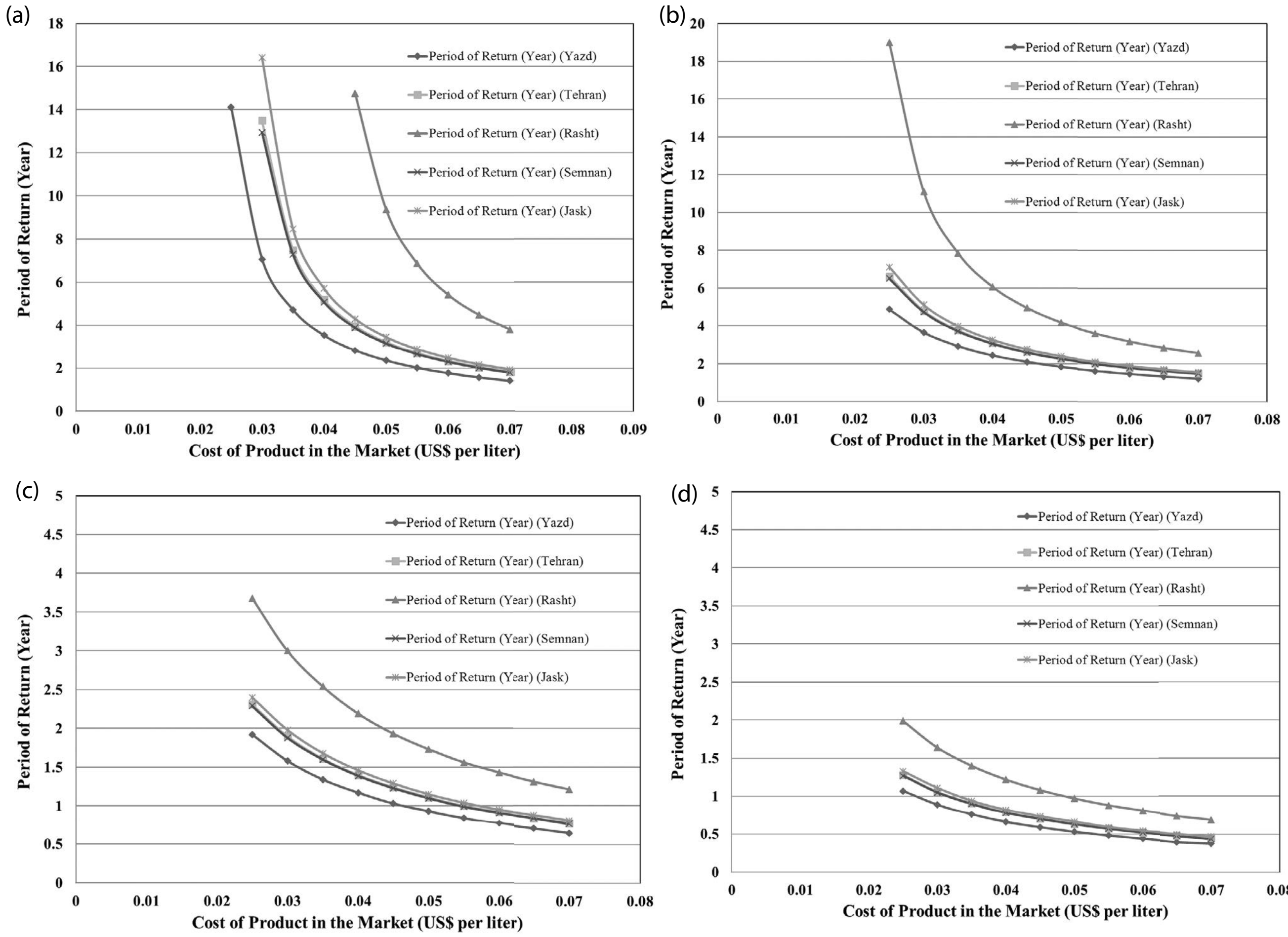


Fig. 14. Variation of period of return during different size and in selected cities (a) Size of 500 L/d, (b) Size of 1,000 L/d, (c) Size of 10,000 L/d, and (d) Size of 100,000 L/d.

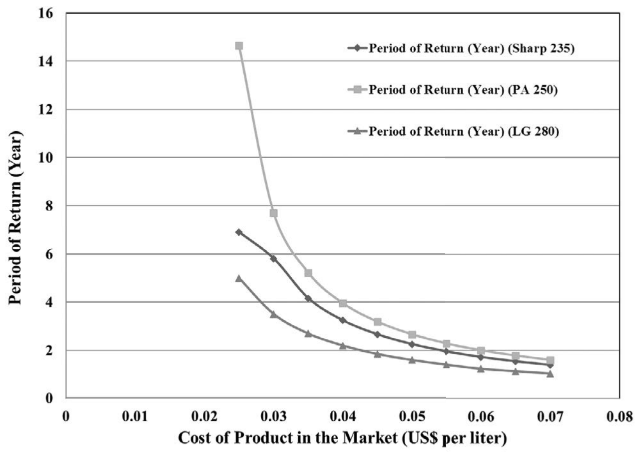


Fig. 15. Variation of period of return during the cost of market in the three suggested solar PV panels.

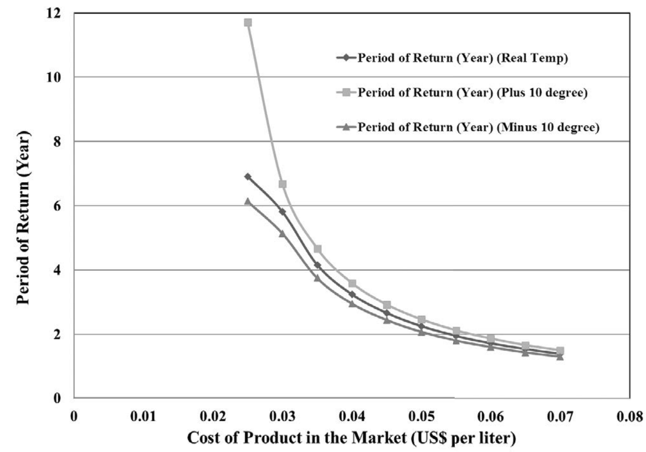


Fig. 16. Effect of ambient temperature in the economic analyses.

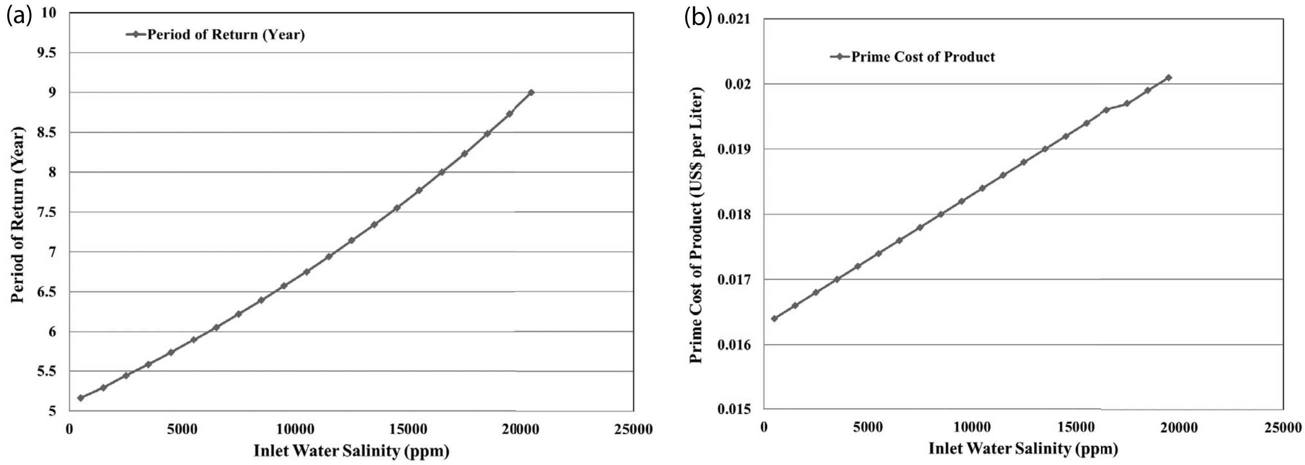


Fig. 17. Effect of inlet water salinity in the economic analyses (a) Effect of inlet water salinity on the period of return and (b) prime cost of product.

have more effective at lower cost of product, so the temperature effect is negligible upper than 0.035 US$/L.

## Symbols

$\bar{I}_T$ — Solar radiation, MJ/m$^2$
$\bar{K}_T$ — Clearness index
$\bar{H}_d$ — Monthly average daily radiation on horizontal surface, MJ/m$^2$
$\bar{H}_0$ — Average clear-sky daily radiation, MJ/m$^2$
$R_b$ — Solar radiation index
$\rho_g$ — Reflection factor
$\omega$ — Hourly angle, rad
$\omega_s$ — Sunset hourly angle, rad
$\beta$ — 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/m$^2$
$V_t$ — Thermal voltage of solar panel, V
$G^*$ — Reference solar radiation, MJ/m$^2$
$V_{charge}$ — Battery charge voltage, V
$V_{discharge}$ — Battery discharge voltage, V
$i$ — Battery current, A
$E_0$ — Battery constant voltage, V
$K$ — Battery polarization constant, Ah$^{-1}$
$Q$ — Maximum battery capacity, Ah
$A$ — Exponential voltage, V
$B$ — Exponential capacity, Ah$^{-1}$
SEC — Specific energy consumption, kWh/m$^3$
$P_{sys}$ — RO working pressure, Pa
$Y$ — RO permeate product water recovery
$\rho$ — Fluid density, kg/m$^2$
$A_p$ — Pipe cross sectional area in RO system, m
$A_m$ — Active membrane surface area in RO system, m
$K_m$ — 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
$f_{os}$ — Membrane index
$C_{feed}$ — Inlet water salinity, ppm
$Q_p$ — Product flow rate, m$^2$/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$/m$^2$
VOP — Volume of product, m$^3$
OFC — Operating flow costs, US$
PC — Prime Cost, US$
AB — Annual benefit, US$
CC — Capital cost, US$

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