International Journal of Smart Energy Technology and Environmental Engineering
Volume 4, Issue 1, March 2025
https://setee.globalpublisher.org/
http://globalpublisher.org/journals-1007/

Investigating a combined desalination and solar power plant system from an energy perspective

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ABSTRACT

Renewable energies such as solar energy and wind energy are important energy sources that have received special attention in recent years due to the increase in fossil fuel prices. The purpose of this paper is to use solar energy for desalination energy in a specific location. In this study, a thermodynamic and economic analysis of a combined RO desalination system with solar panels has been carried out. Fresh water from the sea using water pretreatment and reverse osmosis system can meet the demand for fresh water for a large part of the island. In this study, the desalination plant is considered to be about 72 cubic meters per day for the purpose of fresh water for the urban area (about 400 people). Based on the results, the TDS of the system effluent and the recovery percentage will be 141.3 mg/L and 60.3%, respectively. Also, considering the environment and simulation results, 15228 solar panel units are proposed for the use of consumed electricity in the best case.

Keywords: reverse osmosis, solar panel, membrane, Kish Island, simulation

1. INTRODUCTION

Desalination methods are derived from the mechanisms and processes of rainfall. Researchers first produced fresh water from seawater in the mid-1950s, but the flow was so low that it could not be commercialized [1] .In 1979, Petersen and colleagues evaluated the performance of a reverse osmosis system with a solar panel with a capacity of 1.5 cubic meters per day. In this research, in addition to the RO-PV system, the reverse osmosis system with a wind turbine with a capacity of 9 cubic meters per day has been evaluated [2]. PV-RO technology, which is a combination of RO water treatment and solar panels, is a very good method. In reverse osmosis systems with solar panel, the power required for the reverse osmosis process, which includes the power of the pumps, is provided by photovoltaic panels. From an economic point of view, reverse osmosis systems with solar panels are more efficient than reverse osmosis systems with diesel generators [3]. Herold and colleagues developed three energy management approaches for the PV-RO system [4]. In the work of Thomson and his colleagues, in order to desalinate seawater, a reverse osmosis system with a solar panel has been used. The cost of water production by this system has been about $ 2.64, which the reliability of the water produced has not been reported [5]. The independent wind-solar system with reverse osmosis system was simulated by Mohamed et al. According to this research, the cost of fresh water production by hybrid system is less than PV-RO system. This is because wind energy costs less than solar panels [6]. Computer simulation of a solar panel-based reverse osmosis system was conducted by Hrayshat et al. In 2008 for 10 different locations in Jordan, showing that environmental conditions and saline water entering the system are among the most important parameters that have a significant impact on system performance [7]. In 2010, Khayet and colleagues designed a reverse osmosis system with a solar panel and a solar thermal power plant. In this system, in addition to the solar panel, thermal energy is also used to generate power. This system includes high pressure and low pressure pump, polyamide composite membrane with a diameter of 1.2 square meters, spherical heat collector. The optimal amount of feed pressure, volume rate and temperature for the concentration of 6 g / l are equal to 7.7 bar, 252.8 l / h and 33 ° C, respectively [8]. In 2011, Davies proposed a new system that uses a Rankine solar cycle for guidance (RO) [9]. Pascale offers various solutions for the most common desalination process (RO, MSF, MED) and solar energy generation technology compatible with desalination. The purpose of the feasibility study is to replace the fuel energy used for desalination plants with renewable energy. A review of different technologies generally defines the features associated with each technology and the expected cost range. Finally, a review of the various projects describes the practical details of the floor space and the actual costs of producing fresh water [10]. The efficiency of a PV-RO system depends on the efficiency of all components in the system. Cost of water production and energy consumption of purification systems that work with solar panels. According to studies and available equipment, PV-RO systems are very suitable for small-scale water treatment and are not recommended for medium and large-scale treatment [11]. In 2017, Shalaby stated that when energy recovery devices are used, there is no need to preheat the feed water, especially in the case of PV-RO systems. Most RO power plants currently operate on PV, although the PTC-ORC-RO desalination system is recommended, but has not yet been implemented on a large scale [12]. In 2018, Islam et al. Propose a creative hybrid system, which is based on reverse osmosis solar energy, the inclusion of a cooling system increases the energy efficiency and energy of PV panels. In this system, the demand for electricity and fresh water in the regions Off-grid is supplied through renewable energy [13]. In 2019, Ejaz showed that rising water demand has led to a rapid increase in desalination installations around the world, and that solar-powered desalination provides a sustainable solution to meet water needs. The compatibility of any desalination process with solar technology is due to the thermal or electrical type of energy required and also its availability [14]. In 2019, Chen et al. Discussed water resources and the use of solar energy in China, and provided a comprehensive review of a possible solution. In their study, potential desalination methods are compared with solar energy [15]. In 2019, Mito et al. Identified potential challenges and solutions for large-scale RO desalination managed by renewable energy sources. This review presents the most advanced RO mode with solar and PV to identify technical challenges and potential solutions for large-scale implementation [16]. In 2020 Abbassi reviewed a new system in Egypt and showed that increasing the efficiency of PVT requires fewer panels due to cooling, and the reduction in energy consumption per reverse osmosis unit is 0.12 kWh per cubic meter [17]. In 2021, Rahimi and his colleagues examined the effects of energy recovery devices and batteries and showed that using energy recovery devices in any scenario is not cost-effective and the worst case scenario is one that uses batteries [18]. Small-scale desalination is also very important, Javadi et al. Showed, small-scale solar-based desalination is one of the promising technologies to address this problem. In their report, several solar still systems are examined. All systems have the same condenser, but each system is used by different heating devices [19]. Fresh water production is very important in Kish Island. In 2021, Ahmadi et al. Showed that the MED-TVC desalination system is one of the most suitable and economical desalination systems. In this study, the combination of Allam cycle and desalination system is used on Kish Island, located in southern Iran. The results of this study show that the proposed cycle has a good economic performance, the net present value (NPV) shows that the payback period in this plan is 4.8 years [20]. In desalination systems, the concept of exergy and economy are very important. Nazarzadehfard et al. Performed an exergy and thermoeconomic analysis of a hybrid desalination system (MED) and the Allam power generation system. They showed that, ideally, the price of fresh water using steam generated by a boiler is $ 1,131 per cubic meter and with steam generated by a power generation system is $ 1,087 per cubic meter. Hence, the results show that the combination of the desalination system with the Allam production system provides 4% reduction. Reducing carbon dioxide emissions is also a significant advantage of this system [21]. The purpose of this article is to use solar energy to supply desalination energy in Kish Island. In this study, thermodynamic and economic analysis of a combined RO desalination system with a solar panel on Kish Island has been performed. Kish Island does not have a permanent river and on the other hand, using solar energy on Kish Island as a tourism hub, has an effective role in preserving the environment and increasing the attractiveness of the island.

2. MODELING

Figure 1 shows the structure intended for reverse osmosis water treatment with a solar panel. First, the optimal reverse osmosis system is determined and then, according to the uses of this system, the photovoltaic unit is modeled.

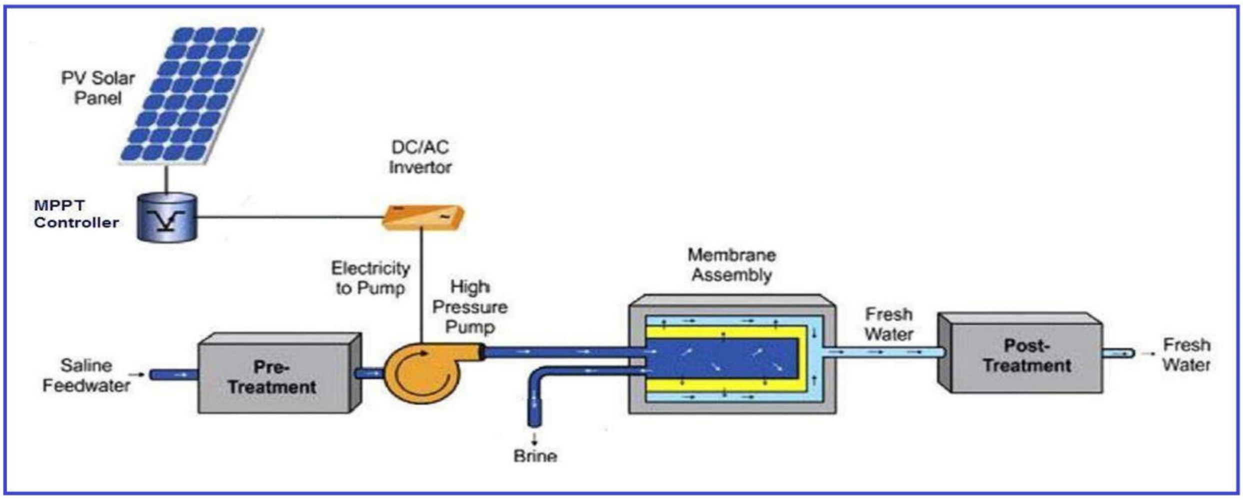

Figure 1 - Schematic of reverse osmosis system - photovoltaic direct connection [22]

In order to simulate the solar panel, it is first necessary to select the required capacity to produce purified water and then design a reverse osmosis system. In order to simulate, it is first necessary to determine the composition of the incoming water, which is the water of the Persian Gulf. In order to sweeten, it is first necessary to use UF pretreatment and then enter the reverse osmosis system. After examining the reverse osmosis system, the next step is to calculate the power consumption of the reverse osmosis system. Using the required pressure values of the incoming water as well as the required water rate, the power consumption can be calculated. In the final step, the solar system is simulated according to the required power consumption. The composition of seawater near Kish Island is as shown in Table 1.

Table 1- Persian Gulf water composition [22]

Parameter	Concentration (mg/L)
HCO3 Bicarbonate Alkalinity	**115**
CO3 Carbonate Alkalinity	**20**
Total Calcium (Ca)	**412**
Total Magnesium (Mg)	**1280**
Total Potassium (K)	**399**
Total Sodium (Na)	**10500**
Sulfate (SO4)	**2700**
Barium (Ba)	**0.0458**
Boron (B)	**0.986**
Chloride	**19000**
Fluoride	**1.3**
TDS	**39200**

It is necessary to use pre-treatment before the reverse osmosis system. It should be noted that reverse osmosis membranes alone are not able to supply drinking water for consumption and do not guarantee the high efficiency of the desalination system. The desalination system includes all the steps used before the water reaches the reverse osmosis membranes. These steps increase the useful life of the desalination plant and also reduce the need for chemical washing of membranes and even the frequency of membrane replacement. Therefore, it directly affects the performance of a desalination system. There are various pollutants in the water. Some of these contaminants should be removed before entering the reverse osmosis system to increase the length and quality of the reverse osmosis filters in addition to affecting the final water quality. These contaminants can include suspended solids, gases, and heavy metals. These contaminants are removed in the pre-treatment stage by filters such as sand filters and carbon filters. The seawater pre-treatment system is considered so that the output of the system is in accordance with Table 2.

Table 2- Water composition after pretreatment [22]

Parameter	Concentration (mg/L)
HCO3 Bicarbonate Alkalinity	**115**
CO3 Carbonate Alkalinity	**20**
Total Calcium(Ca)	**56.5**
Total Magnesium(Mg)	**235**
Total Potassium(K)	**399**
Total Sodium(Na)	**10500**
Sulfate(SO4)	**458**
Barium(Ba)	**0.0458**
Boron(B)	**0.986**
Chloride	**19000**
Fluoride	**1.3**
TDS	**32142**

Reverse Osmosis System

The SFD-2660 model is used in this system. These examples of ultra-filter systems have high strength and have a hollow structure. Using these ultrafiltrations, bacteria, viruses and particles up to 0.03 micrometers in diameter can be easily removed from the water.

Figure 2 shows a schematic of the ultrafiltration system.

The membranes in these systems are able to easily remove colloidal particles in the water and sweeten the water. These systems are used in industrial desalination plants as pre-treatment. The fibers used in this type of ultrafiltration membranes are made of hydrophobic PVDF and are porous.

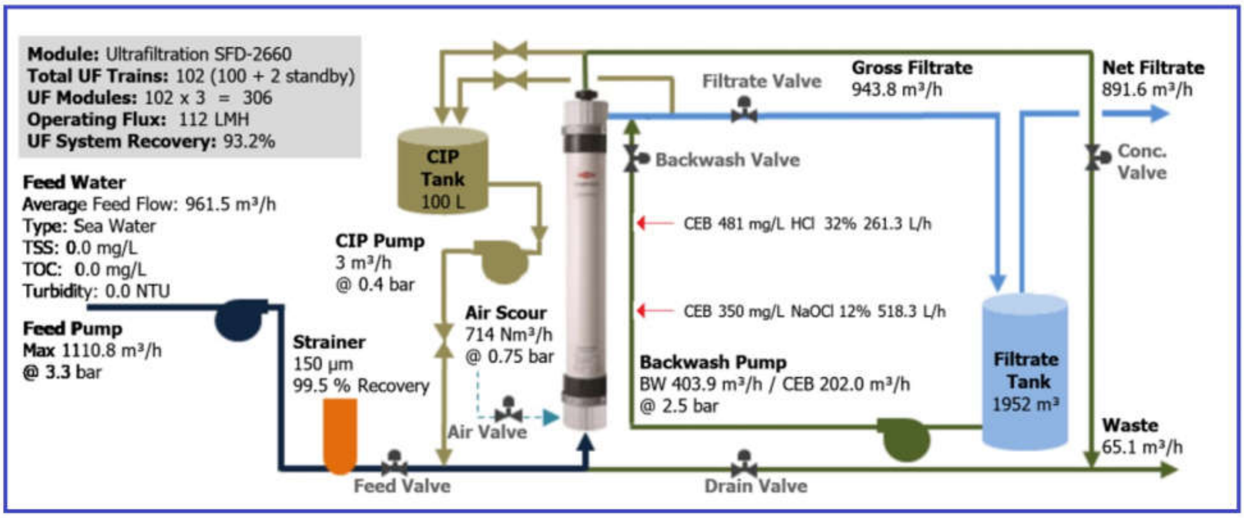

Figure 2 -schematic of ultrafiltration [22]

3. GOVERNING EQUATIONS

Osmosis pressure is calculated from Equation 1, the flow rate and NDP can also be calculated from Equations 2 and 3.

$$P_{osm} = 1.19\,(T + 273) \times \sum m_i \quad (1)$$

$$Q_w = (\Delta P - \Delta P_{osm}) \times K_w \times \frac{S}{d} \quad (2)$$

$$Q_w = A \times (NDP) \quad (3)$$

Q_w : Flow rate
ΔP : Hydraulic pressure difference
ΔP_{osm} : Osmosis pressure difference
K_w : Membrane permeability coefficient
S : Membrane surface
d : Membrane thickness
NDP: Net driving pressure differential
Equations (4), (5) and (6) can also be used to calculate the volume flow rate of salt, salt passage and permeate recovery rate.

$$Q_s = \Delta C \times K_s \times S/d \quad (4)$$

$$\mathrm{SP} = 100\% \times \left(\frac{\mathrm{C_p}}{\mathrm{C_{fm}}}\right) \quad (5)$$

$$\mathrm{R} = 100\% \times (\mathrm{Q_p}/\mathrm{Q_f}) \quad (6)$$

Q_s : Volumetric rate of salt in the membrane
K_s : Membrane permeability coefficient

ΔC : Difference in salt concentration on both sides of the membrane
S: Membrane surface
d: Membrane thickness
SP: Salt Passage
R: Permeate Recovery Rate
Membranes used in desalination unit
In order to investigate the effect of different membranes on the quality of treated water in Kish Island, the following four types of membranes are used.

- SW30HRLE-440i
- SW30ULE-400i
- SW30HRLE-370/34
- SW30HR-380

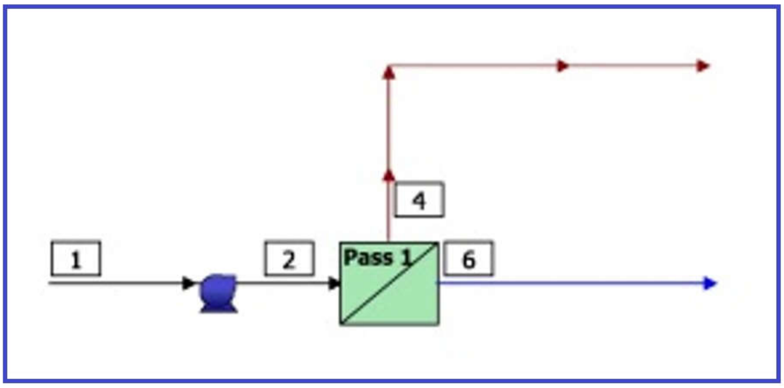

Figure 3 - RO system membrane diagram [22]
In this section, the required inlet flow pressure is investigated in four cases. In fact, in order to calculate the power required for the reverse osmosis system, it is necessary to determine the inlet flow pressure and volume rate.
Table 3 shows the required pressure, water volume rate and Recovery percentage in four cases.
Table 3 - Required pressure, volume rate and percentage of inlet flow Recovery [22]

	Recovery (%)	TDS	Input volume rate (m3/h)	Number of membranes	Pressure (bar)
Membrane-1	60.3	141.3	866.8	560	**80**
Membrane-2	65.7	392.4	866.8	720	**80**
Membrane-3	56.9	116.9	866.8	560	**80**
Membrane-4	61	222.0	866.8	720	**80**

Due to the fact that the TDS of drinking water should be less than 150 mg / l, first and third state membranes can be used. Considering that in the first mode of the membrane (SW30HRLE-440i) with a pressure of 80 bar, the recovery percentage is 60.3% and the amount of TDS output is in the range of drinking water, this mode has been selected as the optimal mode.
The maximum tolerable pressure of these membranes was 83 bar, which allows desalination of water with high salinity.

Table 4 - Performance study of SW30HRLE-440i membrane [22]

#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to Pump	869.9	32,142	0.0
2	Net Feed to Pass 1	866.8	32,255	80.0
4	Total Concentrate from Pass 1	343.8	81,105	77.9
6	Total Permeate from Pass 1	524.9	141.3	0.0

RO System Overview

Total # of Trains 1	Online = 1	Standby = 0	RO Recovery
System Flow Rate (m^3/h)	Net Feed = 869.9	Net Product = 524.9	60.3 %

In the first case, 8 elements of the SW30HRLE-440i membrane are used in one step. The input of seawater is 869.9 cubic meters per hour and the output of water is equal to 524.9 cubic meters per hour with an efficiency of 60.3%.

Table 5 - SW30HRLE-440i membrane Performance (each element) [22]

RO Flow Table (Element Level - Pass 1)

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30HRLE-440i	13.7	12.4	79.7	32,255	10.7	1.69	41.3	52.42
1	2	SW30HRLE-440i	13.9	10.7	79.3	37,324	9.20	1.48	36.3	68.32
1	3	SW30HRLE-440i	13.6	9.20	79.0	43,294	8.00	1.25	30.7	91.72
1	4	SW30HRLE-440i	12.7	8.00	78.7	50,067	7.00	1.02	24.8	127.0
1	5	SW30HRLE-440i	11.3	7.00	78.5	57,326	6.20	0.78	19.2	181.1
1	6	SW30HRLE-440i	9.3	6.20	78.3	64,549	5.60	0.58	14.1	265.3
1	7	SW30HRLE-440i	7.3	5.60	78.2	71,143	5.20	0.41	10.0	395.4
1	8	SW30HRLE-440i	5.5	5.20	78.0	76,697	4.90	0.29	7.0	590.2

On the other hand, it is necessary that the capacity of the desalination system be equal to the water consumption capacity of the population of Kish. The urban population of Kish is approximately 39853 people and water consumption in Iran is equal to 180 liters per person per day. Therefore, the capacity of the desalination system should be at least equal to 7173 cubic meters per day.

According to the desired results of the first mode of the membrane (in terms of pressure drop and TDS output), this mode is used. According to Table 3, the Recovery rate in this case is 60% and the required pressure is 80 bar. According to the Recovery percentage of the first case, the amount of incoming water should be equal to Equation 7.

$$Q = 7173\,\frac{m3}{day} \times \frac{1}{0.60} \times \frac{1}{24}\,\frac{day}{h} = 498.1\,\frac{m3}{h} \qquad (7)$$

Pre-Treatment System

In order to calculate the production capacity of the power plant, in addition to high pressure pumps of reverse osmosis system, it is necessary to determine the major uses in the pre-treatment system. Most

of the energy is spent on the water transfer phase, which requires that seawater be pumped to a pre-treatment unit. The height of the selected location is 6 meters above sea level. The average height of the island at a distance of one kilometer from the coast is about 11 meters. After passing the pre-treatment stage, the feed water enters the desalination section by a pump. Since the above main pumps are an essential component of any RO system, the design and selection of these pumps should be such as to provide the desired current intensity at the desired system pressure for the membrane. In this study, a submersible pump has been selected, this pump belongs to the BRVS 486 submersible pump group. These pumps consist of two parts. An engine that provides the nominal power required to pump water and a pump that pumps water to the intended height by rotating the impellers inside the pump body.
This pump has a maximum rate of 460 cubic meters per hour and a height of 39 meters at its maximum efficiency. Due to the fact that the required volume rate is 869.9 cubic meters per hour, two 486 / 1a pumps are used.

4. RESULTS AND DISCUSSION

Once the pressure and volume rate required by the reverse osmosis system are known, the pump required for the reverse osmosis system is determined. The 150 WKL three-stage pump is the best choice for a reverse osmosis system. In order to start the reverse osmosis system, two three-stage 150 WKL pumps are required, and the volume rate of each pump is 150 cubic meters per hour. Therefore, in the case that the reverse osmosis system has the highest performance, the power consumption of the system reaches 420 kW. The annual power consumption for a system is 3,628,800 kWh, and finally the two systems are considered to be 7,257,600 kWh.

5. CONCLUSION

The purpose of this article is to solve the water quality problem of the area based on the design of a solar water desalination system that is a good option for the area and also based on environmental conditions. The proposed reverse osmosis-photovoltaic system is a direct connection system. This means that in this system, after receiving energy from solar radiation by the photovoltaic system, the reverse osmosis system also starts working. The reason for choosing this type of connection is that as the intensity of solar radiation increases in the middle of the day, the volume rate of water produced will be higher and because the maximum daily consumption occurs in the middle of the day.

This increase in water withdrawal from the network and the increase in water production almost coincide, and it seems that there will be no shortage in this area. It is also obvious that in the hot months of the year, water harvest is more than the average per capita consumption, water production increases due to the increase in intensity and number of hours of solar radiation, and this overlap and matching of consumption and production is a positive point of direct connection systems. In this study, the capacity of the desalination plant is approximately 7200 cubic meters per day in order to supply fresh water to the urban population of the island (40,000 people). In order to design the desalination unit and supply it with energy, first a suitable membrane was determined from the simulation results and the power consumption of the system including pretreatment and reverse osmosis system was calculated to be 9,620,000 kWh of energy per year. According to the results, the TDS of fresh water of the system and the percentage of Recovery will be 141.3 mg / l and 60.3%, respectively. Also, due to space constraints and simulation results, in order to provide power consumption, in the best case, 15228 solar panel units have been proposed.

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