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Design and analysis of a solar photovoltaic powered seawater reverse osmosis plant in the southern region of the Gaza Strip

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ABSTRACT

Energy and water are essential components to any civilization. Both are important for industrial, agricultural and societal development. Desalination seems to be one of the most suitable solutions to the water problem. The integration of renewable energy into water desalination systems has become increasingly attractive due to the growing demand for water and energy. In this paper, a proposed model consists of a solar photovoltaic (PV) powered seawater reverse osmosis desalination plant for the southern region of the Gaza Strip. The proposed system of reverse osmosis plant with a capacity of 2,400 m^3/h is designed using ROSA software. As the solar PV plant is designed using System Advisor Model software that does not rely on expensive batteries, the water production cost is nearly the same as the current expenses (0.56 USD/m^3). The simple payback period for PV plant was found to be 5.9 years, the nominal levelized cost of energy was 9.3 cents/kWh, the net present value was around $800,000 and the investor internal rate of return was 10.6% (which is greater than the interest rate 6%). The system reduces the emission of greenhouse gases. Comparing the results obtained with the conventional values, this model would provide a much needed efficient compensator of the shortage of water and energy, making it more sustainable and economically feasible.

Keywords: Desalination; Reverse osmosis (RO); Solar photovoltaic (PV); Cost analysis; Renewable energy; Gaza Strip

1. Introduction

Water and energy are crucial for maintaining environment and ecosystem conducive to sustain all forms of life [1]. They play a vital role in meeting the basic human needs of life and health as well as those of social and economic development.

The shortage of water and energy resources in the Gaza Strip has become a great concern. Fears and anxieties are increasing due to rapid depletion of conventional water resources as a result of domestic and agricultural activities [2].

The most promising solution to overcome the water deficiency is desalination. Desalination is defined as the process of removing dissolved salts and minerals from saline water to produce potable water [3]. Saline water can be classified depending on the total dissolved solids (TDS) into brackish water, with TDS reaching up to 10,000 ppm and seawater, with TDS up to 45,000 ppm [4]. The permissible limit of salinity in potable water is in the range of 500–1,000 ppm [5]. However, desalination extensively consumes energy; it requires about 10,000 tons of fossil fuel per year to produce 1,000 m^3 of water each day [6]. Replacing the depleted fossil fuel by renewable and sustainable energy resources has become an urgent need to decrease the carbon footprint and greenhouse gases (GHG) emission, which are the main causes of global warming and climate change [3].

In recent years, there has been considerable growth in the utilization of RO processes in major desalination plants [7,8]. An RO purification system uses a semi-permeable membrane to remove ions, proteins and organic chemicals which are generally not easily removed using other conventional treatment methods [9]. RO has been widely used for various water

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and wastewater treatment processes [7,10,11]. Typically in an RO plant, the production of 1 m^3 of freshwater from seawater uses 3–5 kWh of electricity, and between 0.5 and 2.5 kWh of brackish water [12,13]. In fact, according to the last report of the International Desalination Association, around 80% of desalination plants currently use RO as their separation technology. This technology is successful because it has higher water recovery factor, lower energy consumption, and lower water cost than any conventional process [14].

Energy plays an important role in the RO desalination process. Renewable and sustainable energy resources are crucial for powering the desalination plant [15]. Solar energy, as a major renewable and eco-friendly energy source with the most prominent characteristic of inexhaustibility, is currently promising in terms of offering potential solutions for seawater desalination. One of the most common solar technologies nowadays is solar PV, which significantly contributes to the energy supply around the world [16]. Solar irradiation, temperature and wind speed are the main environmental factors affecting PV [17,18]. A PV system typically consists of a solar cell array [19]. It might also include other elements depending on the requirements or needs of the users of the generated energy. The elements that perform the conditioning of the power output of the PV plant are commonly referred to as the balance of system components, and are an integral part of a PV plant [20]. Sunlight can be directly converted into electric energy by PV panels [21]. A solar PV energy source should be combined with other energy sources and used either as a stand-alone or in grid connected mode. Stand-alone energy systems are very popular, especially in remote sites [22].

2. Study area

The Gaza Strip is an elongated zone located at the south-eastern coast of Palestine with coordinates of latitude N31° 26′ 25″ and Longitude E34° 23′ 34″. It is located in the south east corner of the Mediterranean Sea. The length of the Gaza Strip shore on the Mediterranean is about 41 km and the width ranges from 5 km in the middle to 8 km in the north and 12 km in the south as shown in Fig. 1. According to the Palestinian Central Bureau of Statistics (PCBS), the population of the Gaza Strip Governorates was around 2 millions in mid-2017. The natural rate of increase of the population was 3.44% [23].

For many years now, the Gaza Strip has been suffering from a chronic crisis in the water and energy sectors. The desalination of seawater using renewable energy has become one of the most important methods for providing potable water to citizens in the Gaza Strip. Therefore, a seawater reverse osmosis (SWRO) desalination plant powered by solar PV is proposed to meet the water and energy needs for the southern region of the Gaza Strip (Khan Yunis and Rafah).

2.1. Water problem statement

According to the Palestinian Water Authority (PWA), the Coastal Aquifer in the Gaza Strip receives an average annual recharge of 50–60 MCM/year, mainly from rainfall, while the total extracted volume is about 185 MCM/year (about 102 MCM/year for municipal/domestic use and about 83 MCM/year for agricultural use) [25]. These unsustainably high rates of extraction have lowered the groundwater level, increased the gradual intrusion of seawater and upwelling of saline groundwater, and worsened pollution due to increased nitrate and chlorine levels in the groundwater [26–28].

2.2. Energy problem statement

The Gaza Strip receives most of its electric power 120 MW from Israel, while up to 60 MW are produced at the only power plant in Gaza when operating two out of its four turbines and 28 MW are imported from Egypt. Under ideal circumstances, this adds up to 208 MW against a peak demand of up to 450 MW [29,30]. The Gaza Electricity Distribution Corporation (GEDCo) expects the electricity demand to increase to 550 MW by 2020, which is more than twice the amount that is being currently provided. The Gaza Strip has suffered from a continuous electricity deficit with the current deficit standing at approximately 65% [31].

2.3. Potential of solar energy in the Gaza Strip

The Gaza Strip has a high potential of solar energy during the year. The important parameters are solar potential direct normal irradiation, which is relevant to solar concentrators, and global horizontal irradiation (GHI), which is also often considered as a climate reference of any site. Diffuse and direct components of global tilted irradiation (GTI) or GHI

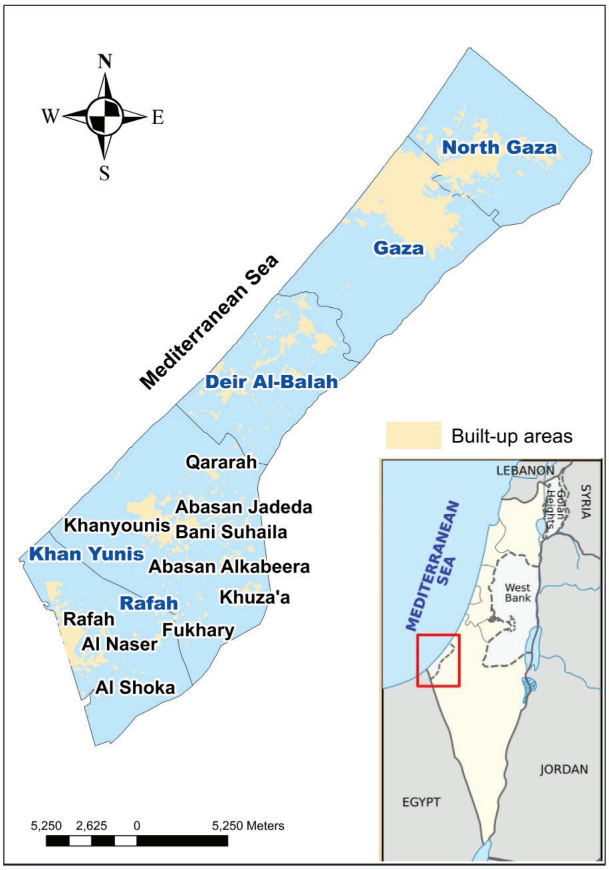

Fig. 1. Gaza Strip and governorates.
Source: Adapted from [24].

indicate how different types of PV technology may perform. The most important parameter for PV potential evaluation is GTI, that is, the sum of direct and diffuse solar radiation falling at the surface of PV modules [32].

The regional trend of GTI is similar to GHI. The optimum tilt (inclination) of PV modules in the Gaza Strip can result in a yield of up to or even more than 2,300 kWh/m^2 of global tilted irradiation per year [32].

3. Methodology

To design the proposed SWRO plant powered by PV, documentary data were collected from several governmental and nongovernmental organizations and institutions. The collected information included policy statements, ministerial or departmental annual reports, legislations, and the energy sector letters and procedures. The data were used to estimate the consumed water. Part of the data was used in the ROSA software and another part was used in the System Advisor Model (SAM).

The ROSA program has been used to design the south seawater desalination plant (SSDP) using part of the collected data. The results of the program gave preliminary estimates of the amount of electricity required to desalinate the amount of water needed in the south region and predicted the brine and permeate characteristics and the minimum specific energy consumption that can be achieved using the pressure exchanger (PX) device.

Based on the electricity needed by the SWRO plant for the southern region, as estimated by the ROSA program, a new version of SAM (2016.3.14, 2017.1.17) (SAM 2016.3.14, 2017.1.17) program issued by the National Renewable Energy Laboratory) has been used in designing and calculating the feasibility of using the solar PV plant to power the proposed SWRO plant based on the intensity of radiation and weather data in the Gaza Strip. According to the result from the SAM program, initial cost analysis has been used based on the most important parameters for the PV plant such as internal rate of return (IRR), payback period, levelized costs of electricity (LCOE) and net present value (NPV).

4. South seawater desalination plant model powered by PV

According to the PWA, the water consumption in the Gaza Strip until 2020 is about 100 L per capita per day (L/c/d), and according to the World Health Organization (WHO) standards, at 100 L/c/d all requirements can be met [33]. This value will be the basis to estimate and calculate the amount of needed desalinated water for the South Governorate Seawater Desalination Plant, as shown in Table 1.

Table 1
Amount of domestic water consumed in the southern region

Governorate	Population	Consumption L/c/d	Total water consumption MCM/year
South of the Gaza Strip	585,424	100	21

The south governorate seawater desalination plant serves the following areas (Al-Qarara, Khan Yunis, Bani Suheila, Abasan al-Jadida, Abasan al-Kabira, Khuza'a, Al-Fukhari, Al Naser, Al Shoka and Rafah).

4.1. Reverse osmosis south seawater desalination plant

The annual capacity of the SSDP plant, according to Table 1, is about 21 MCM/year for drinking and domestic uses. This is equal to 2,400 m^3/h.

4.1.1. Reverse osmosis plant model

A ROSA 9.0 software has been used to design the RO SSDP plant. The plant is designed considering the requirements of the southern region of the Gaza Strip (2,400 m^3/h). The seawater properties in the Gaza Strip were used (seawater TDS is about 38,000 mg/L [28]). The design includes a pretreatment process in which fouling elements would be removed. Considering the required capacity, a single-stage plant has been designed. The number of elements in each pressure vessel was considered to be eight. Therefore, the selected temperature was 25°C to design for the maximum power requirement. An efficiency of 45% is considered. To achieve the greatest possible energy saving power supply, a PX was chosen with energy savings of 50%–60%. The RO analysis conducted using ROSA 9.0 software suggested that a specific energy of 3–3.5 kWh/m^3 would be needed. The main input and output features and results for the model are shown in Tables 2 and 3, respectively.

The TDS in the permeate is 188.6 mg/L, which enables municipalities to mix it with brackish water to reduce the cost per m^3.

Table 4 illustrates the values of all elements in the permeate, the feed, the adjusted feed and the water concentrate

Table 2
Main ROSA input feature for the SSDP model

Permeate flow	2,400.03 m^3/h
Feed pressure	57.97 bar
Feed TDS	38,401.69 mg/L
Element	SW30XHR-440i
Number of elements in each pressure vessel	8
Feed temperature	25°C

Table 3
Main output result and feature obtained from ROSA software for the SSDP model

Feed flow to stage 1 raw water flow to system	5,333.33 m^3/h
Permeate TDS	188.63 mg/L
Cost of water (NPV)	0.56 $/m^3
Specific energy with use energy recovery	3–3.5 kWh/m^3
Number of pressure vessels	670
Number of elements	5,360
Total active area	219,095.36 m^2

Table 4
All elements in the permeate, feed, adjust feed and concentrate water from ROSA software for the SSDP

Pass streams (mg/L as ion)					
Name	Feed	Adjusted feed	Concentrate	Permeate	
			Stage 1	Stage 1	Total
$NH_4^+ + NH_3$	5.59	5.91	10.99	0.40	0.40
K	433.69	433.69	784.64	4.76	4.76
Na	11,729.51	11,729.51	21,273.83	64.48	64.48
Mg	1,439.08	1,439.08	2,615.03	1.85	1.85
Ca	443.56	443.56	806.01	0.56	0.56
Sr	7.88	7.88	14.32	0.01	0.01
Ba	0.31	0.31	0.56	0.00	0.00
CO_3	19.42	19.42	37.25	0.00	0.00
HCO_3	142.07	142.07	254.05	1.11	1.11
NO_3	101.48	101.48	179.88	5.66	5.66
Cl	21,208.47	21,208.47	38,474.98	105.40	105.40
F	5.07	5.07	9.19	0.04	0.04
SO_4	2,841.33	2,841.33	5,164.97	1.39	1.39
SiO_2	5.91	5.91	10.71	0.05	0.05
B	3.15	3.15	5.27	0.57	0.57
CO_2	0.70	0.70	1.55	0.87	0.87
TDS	38,401.37	38,401.69	69,666.16	188.63	188.63
pH	8.00	8.00	7.99	6.26	6.26

for the SSDP model, compatible with local and international standards.

4.2. PV model (plant) of 10 MW

Sunlight can be directly converted into electrical energy by PV panels [21]. The current output of PV panels is a function of voltage and a function of solar radiation. PV generators straightforwardly change over sun-based radiation into electrical energy.

According to Table 3, the estimated specific power to desalinate the required water by using energy recovery is about 8–10 MW. According to the Palestinian Energy Authority, the potential of the PV solar energy in the Gaza Strip is very feasible [32], so a PV plant of 10 MW has been suggested to use solar energy as the energy source for the desalination plant.

A new version of System Advisor Model (2016.3.14, 2017.1.17) (SAM 2016.3.14, 2017.1.17) is used. The SAM program results are shown in Table 5, illustrating the financial model that includes installed costs and total installed costs for the PV plant of 10 MW.

The production LCOE value is 9.3 cents/kWh (Table 5). This value is considered feasible and economically effective compared with the electricity tariff in Palestine (between 14 and 16 cents/kWh [31]).

Table 6 illustrates the performance model for the PV system specifications including the main features. The module type used Mono-c-si with an area of 1.6 m^2 for each module. The quantity of the needed module is 32,232 with a total area of 52,570 m^2. In order to overcome the large areas required for this system, the roofs of agricultural houses are suggested to be used through neighboring agricultural areas.

Table 5
Financial model as a result of SAM program for the PV plant of 10 MW

Installed cost	$1.36/W
Total installed cost	$13,600,000
Project life	25 years
Inflation rate	2.5%
Real discount rate	5.5%
Insurance	0.5%/year
Investor NPV	$800,700
Investor IRR	10.6%
Interest rate	6%
Solution mode	Calculate PPA price
PPA price (year one)	10.1 cents/kWh
Nominal LCOE	9.3 cents/kWh
PPA escalation rate	1%/year
Target IRR	9% in year 9
Developer NPV	$2,475,300
Developer IRR	12%

Fig. 2 illustrates the solar radiation produced every month for the 10 MW PV plant. The highest values of solar radiation are in June, July and August (7.3, 7.16 and 7.15 kWh/m^2/d, respectively), while the lowest values of solar radiation are in January and December (4.38 and 4.26 kWh/m^2/d, respectively).

It is obvious from Fig. 2 that fluctuations of solar daily insolation lead to the fact that solar energy system without storage batteries needs other source of energy. Hence, there

Table 6
Performance model PV system specifications of the 10 MW plant

System nameplate size	10,000 kW
Module type	Mono-c-Si
DC to AC ratio	1.2
Rated inverter size	8,333.3 kW
Inverter efficiency	96%
Array type	Fixed open rack
Total system losses	14.1%
Degradation	0.5%/year
Module area	1.6 m²
Array tilt	27°
Quantity	32,232 module area
Total area	52,570 m²

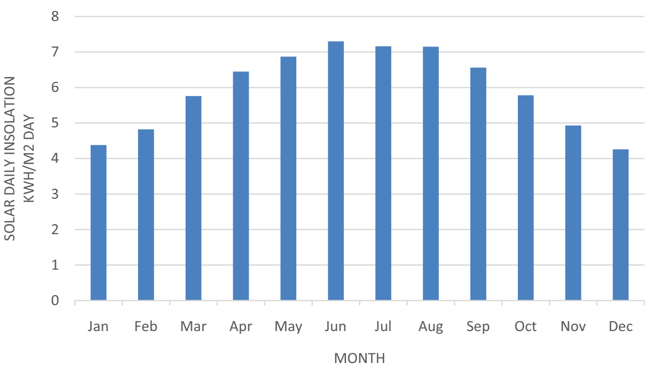

Fig. 2. Solar daily insolation (kWh/m^2 d) for the 10 MW PV plant.

is a need of integrating the solar system with other sources of energy. The deficit of energy, during times with insufficient solar insolation, would be compensated by the grid connection with the PV. On the other hand, the surplus of energy during times of high solar insolation would be used for feeding the public electricity network. This process of integrating solar energy with other sources of energy would guarantee the suitability of power supply to the desalination plant throughout the year.

4.2.1. Initial cost analysis for the PV models

The initial cost analysis estimates the periodic and end-of-life costs of the solar PV system. The basic tools that were used in the initial cost analysis of the solar energy PV models used to supply electric power to the SSDP are LCOE, payback period, NPV and IRR.

4.2.1.1. Levelized cost of energy Electricity tariffs in Palestine are very large compared with many countries around the world and are comparable with those in European countries. As seen in Table 5, the nominal LCOE is 9.3 cents/kWh and the power purchase agreement price is 10.1 cents/kWh for the model. This value is considered very feasible and economically effective, considering that the price in Palestine is 14–16 cents/kWh.

4.2.1.2. Payback period We used the simple payback period time formula as shown in Eq. (1) as follows (it does not include the time value of money) [34].

$$\text{SPP} = \frac{\text{System Cost}}{\text{Annual Energy Delivered} \times \text{Cost of Electricity}} \tag{1}$$

Simple payback period for PV model in south Gaza Strip as shown as follows:

$$\text{SPP} = \frac{\$13{,}600{,}000}{\left(16{,}397{,}573 \text{ kWh/y}\right) \times \left(0.14\$/\text{kWh}\right)} = 5.9\text{y} \tag{2}$$

The simple payback period values for the PV model is nearly 5.9 years, which is considered very feasible. This is due to the intensity of solar radiation and to the high tariff in the Gaza Strip.

4.2.1.3. Net present value The NPV is defined as the present value of future cash flows less the initial project cost. NPV can also be defined as the present value of benefits less the present value of costs. The project is considered feasible when NPV is a positive value. From the financial model of the PV plant (Table 5), the NPV is $800,700 (>0), so the plant is considered feasible according to the NPV tool.

4.2.1.4. Internal rate of return A project is preferable if its internal rate of return is greater than the economic discount rate, also known as the prevailing interest rate. IRR is usually used to assess the desirability of investments or projects. The higher the rate of internal return on the project, the more desirable it is to carry out the project. In Palestine, the average interest rate in the period 2011–2016 was 6% [23].

From the financial model of the PV plant (Table 5), the investor IRR is 10.6% and the developer IRR 12%. Both values are higher than the 6% interest rate, so the model is feasible according to the IRR tool. The model with the highest internal recovery rate may be considered one of the best projects to be undertaken.

5. Conclusion

PV solar desalination energy systems offer a win–win solution to the energy and water problems. This option represents an effective contribution to solving the problem of lack of potable water, as well as securing an important source of energy in light of the severe shortage of electricity in the Gaza Strip. The results of the initial cost analysis show the feasibility of applying PV solar energy with good results. Four tools are used in cost analysis of PV solar system. (1) the nominal LCOE is 9.3 cents/kWh, (2) the simple payback period value is nearly 5.9 years, (3) the NPV is $800,700 (>0), (4) the investor IRR is 10.6% and the developer IRR 12%, the last two values are higher than the 6% interest rate. In addition, the desalination system provides an important source of drinking water with high specifications that conform to the

WHO standards (with TDS 188 mg/L) at prices (0.56 USD/m^3) close to those of non-potable water in the Gaza Strip. This model (desalination using PV solar energy) provides a significant contribution to the rehabilitation of the costal groundwater reservoir in the Gaza Strip. This model is a pilot system to be applied in different regions in the Gaza Strip. One of the main indirect benefits of this model is the reduction of carbon dioxide emissions. PV solar energy systems appears to be one of the most efficient and effective solutions for clean and sustainable energy development to operate desalination plants due to radiation intensity and the number of sunny days during year in the Gaza Strip.

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