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Renewable energy power reverse osmosis system for seawater desalination plant

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ABSTRACT

This project focused on the latest developments in the renewable energy to power a small reverse osmosis (RO) desalination plant which provided a small group of people with freshwater in a remote area in Egypt. The aim of this work is to estimate an optimum energy system required for a water treatment plant that produces 125 L/h (3 m^3/d) at constant daily load profile using one of the renewable energy sources such as solar and wind. First of all, the power required for the reverse osmosis plant to produce 3 m^3 of freshwater per day had been calculated manually and the total plant design had been performed using water application value engine (WAVE) software presented by DOW water and process solutions company. Secondly, for solar and wind energy, PVSyst V6.75 software and manual calculations were used to estimate the daily energy production. Of course solar and wind energy are clean, free, and renewable sources of energy, it depends on the site location. As Egypt has its long coastline, it is highly recommended as a perfect location for desalination plants powered by renewable energy sources. Mersa Matruh governorate was assumed in this study to be the location of the plant.

Keywords: Water desalination; Photovoltaics; PV arrays; Wind turbine; Reverse osmosis

1. Introduction

Freshwater is a fundamental component in our life and is one of the three main ingredients of the environment; air, water, and soil. Unfortunately, lack of freshwater is a problem facing many countries in the Mediterranean region and with the rapid increase in population and standard of living, this problem will increase consequently. Referring to many reports about daily water demand per person, one person consumes nearly 150 L potable water per day. Conventional ways of obtaining freshwater sometimes are not enough to cover water demand needed so, non-conventional ways are the best solution to provide countries with the required amount of potable water daily. One of these non-conventional ways is water desalination technology.

1.1. Desalination markets

Presently the majority of desalinated water comes from seawater sources [1] with a percentage equal to 67%, followed by brackish water at 19%, river water at 8%, and only 6% comes from wastewater sources (Fig. 1).

1.2. Desalination technologies

Water desalination is defined as a process of removing salts and minerals from saline water to convert it into

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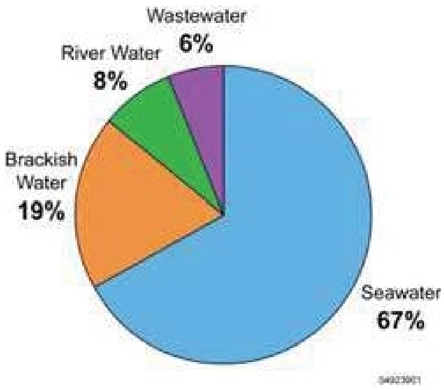


Fig. 1. Worldwide feed-water percentage used in desalination.

potable. Water desalination can occur through different technologies; reverse osmosis, multi-stage flash process, and multi effect distillation. RO technology represents the highest percentage among the other technologies in the global desalination plant capacity, the reason why it was recommended it in this work.

1.2.1. Reverse osmosis

Reverse osmosis has been known as an easy and low cost technology [2]. The process of salt separation from saline water occurs through a semi-permeable membrane which allows only small amount of salt to pass and prevent the other from passing through it.

In this work, the location of a plant to desalinate seawater is assumed to be in Mersa Matruh governorate because of its best location on the Mediterranean Sea coast, Libyan (Western) Desert, in northwestern Egypt.

1.3. Renewable energy sources

Lately price of fossil fuels increases significantly and it becomes difficult to obtain it in some remote areas. For the purpose of reducing fresh air pollution, high attention goes to the use of renewable energy as a source for desalination particularly in the areas where there is a lack of electrical power such as remote areas and islands.

1.4. Desalination–renewable energy integration

There are different combinations between desalination technologies and renewable energy sources [3], we can combine a desalination plant with solar photovoltaic (PV) system, wind turbine system, or hybrid PV-wind system. For the sake of comparison between the cost per cubic meter of desalinated water, solar, and wind energy are used to generate the power required for a small desalination plant in Mersa Matruh, Egypt.

Renewable energy powered by reverse osmosis systems have many reverse advantages, such as lowest operation cost, simple operation, environmentally friendly, easy installation and maintenance, high reliability and suitability for seawater, and brackish water as well. The major renewable energy resources combined with reverse osmosis technology which were discussed and presented in this study: solar energy and wind energy.

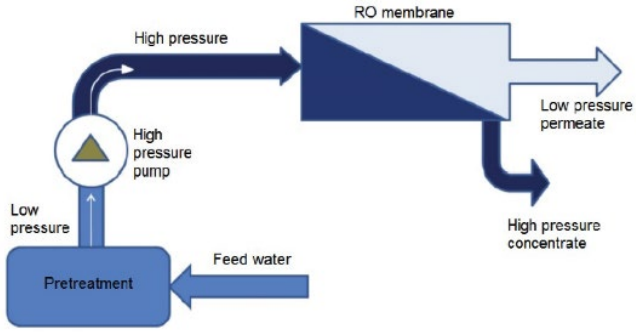


Fig. 2. Schematic of membrane RO systems.

2. Literature review

In the last few years, the use of renewable energy as sources for water desalination had significant attention, especially in the areas where there is a lack of freshwater. The worldwide availability of renewable energies and the availability of mature technologies in this field makes it possible to consider the coupling of desalination plants with renewable energy production processes in order to ensure the production of water in a sustainable and environmentally friendly scheme for the regions concerned [4]. Several references were used [5–23] to indicate the previous work and researches which have been done in the field of integration between renewable energy and reverse osmosis plants.

3. Plant design and sizing

3.1. Methodology

In this study, total specific energy consumption for small RO plant was calculated. Sizing for PV modules and wind turbine as well as batteries for energy storage had been done separately to meet the total energy required.

3.2. Modeling tools

The software modeling tool that was used in this study was water application value engine (WAVE) for RO plant design and PVsyst V6.75 for solar system simulation.

3.3. RO plant

3.3.1. RO system components

The proposed system components are summarized as feed pump, pretreatment stage (multi-media filter and cartridge filter), and RO unit (high-pressure pump, pressure vessel, and membranes). The process flow diagram is shown in Fig. 3.

3.3.2. RO unit operation conditions

RO system was designed to treat with seawater type (with membrane pretreatment, SDI < 3). It was assumed to produce 3 m^3 freshwater daily. Operating hours were assumed to be 24 h/d. Table 1 shows input design technical data for WAVE software.

3.3.3. Calculations of RO plant load

To determine the total daily load required for the RO plant, low and high-pressure pumps required power was calculated using Eq. (1). Pressures and flow rates are shown in Fig. 3.

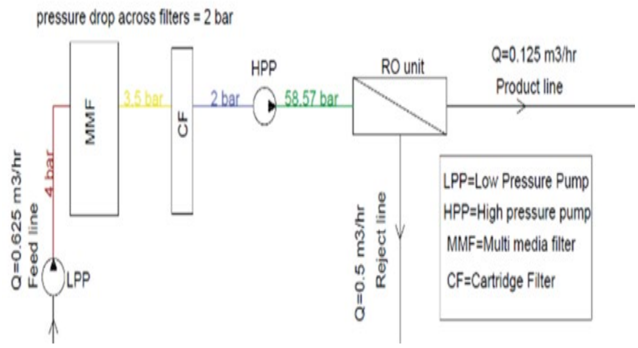


Fig. 3. Process flow diagram.

$$\text{Power} = \frac{P \times Q \times 100}{\eta\ \text{pump} \times \eta\ \text{motor} \times 3{,}600} \quad (1)$$

where P is the pressure (bar), Q is the flow rate (m^3/h), and η is the efficiency.

To calculate the total power needed for RO plant operation for 24 h/d, Eq. (2) was used. Considering in this design DC system efficiency.

Table 1
Input parameters for wave software

Design parameter	Value
Water PH	6.87
Water salinity, mg/L	40,000
Membrane type	SW30-2540
Number of pressure vessels	1
Number of elements per pressure vessel	2
Product flow, m^3/d	3
Recovery ratio R, %	20
Maximum temperature, °C	40
Minimum temperature, °C	10
Design temperature, °C	25

$$\text{The total energy requirement for the RO system} = \frac{\text{Pumps daily watt hours} + \text{Auxiliaries daily watt hours}}{\text{DC system efficiency}} \quad (2)$$

3.4. Solar power system

Solar power system is one of renewable energy system which uses PV modules to convert sunlight into electricity.

3.4.1. Solar system sizing

In this section sizing of PV modules, solar charge controller, and battery bank were done manually using the following equations. Fig. 4 shows the proposed solar system block diagram.

3.4.1.1. PV array

The target of this design is to supply the RO plant with the required energy per day without intermittency. The proposed stand-alone PV system components have been selected and connected in PVSyst simulation. Polycrystalline solar panels are the most used PV panels used. They are offered in a wide range of power ratings, from 5 to 250 WP or more. To calculate the number of PV modules needed to cover the daily load, Eqs. (3) and (4) were used.

$$\text{Total Watt} - \text{peak needed for PV modules} = \frac{\text{Total watt hours for operation}}{\text{PSSH} \times \eta\ \text{battery} \times \eta\ \text{PV thermal}} \quad (3)$$

where PSSH, the peak sunshine hours in the proposed location.

$$\text{Minimum No. of PV modules needed} = \frac{\text{watt peak needed}}{\text{watt peak available}} \quad (4)$$

3.4.1.2. Battery bank

The battery of the PV-RO system was designed to act as energy storage to run the system whenever insufficient solar irradiation is available (cloudy days and nights). Deep cycle battery type was selected.

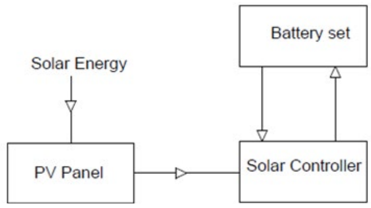


Fig. 4. Solar system block diagram.

Deep cycle battery is specifically designed for to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years. Number of batteries was calculated using Eq. (5).

$$\text{No. of batteries} = \frac{\text{Total watt hours for operation} \times \text{Days of autonomy}}{\text{Battery Ampere} \times \text{nominal voltage} \times \text{MDOD} \times \eta \text{ battery}} \quad (5)$$

where days of autonomy are the number of days that you need the system to operate when there is no power produced by PV panels, MDOD is the maximum depth of discharge.

3.4.1.3. Solar charge controller

The sizing of controller depends on the total PV input current which is delivered to the controller and also depends on PV panel configuration (series or parallel configuration). According to standard practice, the sizing of solar charge controller was done using Eq. (6).

$$\text{Solar charge controller sizing} = \text{No of parallel strings} \times \text{short circuit current} \times 1.3 \quad (6)$$

3.5. Wind turbine

In this study, wind turbine of the horizontal axis, three blades type was designed and selected to meet the daily requirement of RO load. Also sizing of batteries storage was done to feed the RO plant with the required power in case of no power produced from the wind turbine due to bad weather conditions.

Wind speed was an important parameter while assuming the plant location [21]. Table 2 shows that Mersa Matruh is considered one of the best locations in Egypt to establish a desalination plant powered by a wind turbine.

3.6. Wind turbine sizing

Wind turbine should be sized and designed to cover the power needed for RO plant operation and to feed the storage batteries at the same time. To fulfill this design, the capacity of storage batteries as well as number of batteries were calculated manually in the next section.

3.6.1. Battery bank

The total daily power demand for water desalination plants was calculated before using Eq. (2). In battery bank

Table 2
Mean monthly and annual wind speed (m/s) at a height 10 m

Station	Month												Annual mean	Wind direction
	January	February	March	April	May	June	July	August	September	October	November	December		
Sallum	5.4	4.8	5.2	4.3	3.6	4.1	4.7	4.2	3.4	3.6	4.2	5.2	4.4	330 NW
Sidi Barrani	5.6	5.7	5.9	5.7	4.7	4.6	5.2	4.5	4.0	4.2	4.6	5.6	5.0	330 NW
Mersa Matruh	6.1	6.1	6.3	5.7	4.9	5.2	5.2	4.7	4.4	4.3	4.8	5.9	5.3	330 NW
El Dabaa	5.5	5.8	6.1	5.8	5.1	6.0	6.0	5.7	5.0	4.2	4.5	5.5	5.4	330 NW
Dekheila	4.5	4.6	4.9	4.8	4.3	4.5	4.6	4.5	4.2	3.7	3.8	4.1	4.4	360 N
Alexandria	4.4	4.4	4.6	4.3	4.0	4.0	4.4	4.0	3.7	3.1	3.4	4.1	4.0	330 NW
Balteam	3.6	3.5	4.2	4.0	3.5	3.7	3.9	3.6	2.8	2.3	2.6	3.3	3.4	330 NW
Damietta	2.8	3.1	3.7	3.6	3.1	3.1	2.8	2.5	2.3	2.5	2.5	2.9	2.9	330 NW
Port Said	4.8	5.2	5.8	5.4	4.8	4.6	4.3	3.8	3.8	4.1	4.3	4.3	4.6	36 N
El Arish	2.5	2.9	3.0	2.5	2.4	2.4	2.3	2.1	2.2	2.0	2.1	2.4	2.4	330 NW

sizing some assumptions had been taken into consideration to calculate the number of batteries and their needed energy, those assumptions were:

- Days of autonomy were assumed to be equal to 1.5 d.
- MDOD was assumed to be equal to 50%.
- All batteries were connected in parallel and its volt was equal to 12 V.
- Efficiency of batteries in low temperature.

All batteries are less efficient in low temperature and to compensate this, we multiply the power with a factor corresponding to the lowest temperature, Table 3. The suggested factor was 1.19.

Total energy required from storage batteries and total number of batteries were calculated using Eqs. (7)–(9).

$$\text{Total batteries energy} = \frac{\text{Total watt hours for operation} \times \text{Days of autonomy} \times \text{Temperature factor}}{\text{MDOD}} \quad (7)$$

$$\text{Total ampere} = \frac{\text{Total power}}{\text{Total volt}} \quad (8)$$

$$\text{Number of batteries} = \frac{\text{Total batteries power}}{\text{Total ampere} \times \text{Total volt}} \quad (9)$$

3.7. Wind turbine total power

Wind turbine power was determined using Eq. (10). The theory of no wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor [12] has been considered here in wind turbine selection.

$$\text{Wind turbine power} = \text{Water treatment plant power demand} + \text{Battery bank required power} \quad (10)$$

4. Results and discussion

In this section, the results of plant design, analysis, and system energy requirements are described and discussed.

4.1. RO plant

An RO plant was designed to produce 3 m^3/d freshwater. Components of the plant were designed to operate 24 h/d. Table 4 shows the important results from WAVE software which were used for total plant watt-hours basic calculations.

4.1.1. Calculations of RO plant load

Power required for low and high-pressure pumps was calculated by substitution in Eq. (1). For low-pressure pump, feed pressure was assumed to be 4 bar, pump efficiency as 0.6, motor efficiency as 0.9. For high-pressure pump, the pressure drop across pretreatment filters was considered (Fig. 3), pump efficiency was assumed to be as 0.9, motor efficiency as 0.9. By substitution for feed flow rate from Table 4 low and high-pressure pump power were equal to 129 and 1,213 W respectively. Power for auxiliaries was assumed to be 5 W. DC system efficiency was assumed to be equal to 83%. By substitution in Eq. (2), the total energy requirement for the RO-system was determined as (39,000 Wh).

4.2. Solar power system

In order to satisfy the previously calculated RO load requirements, manual calculations as well as simulation had been done for the proposed solar system to feed the RO plant with continuous power supply. The following section discusses the detailed results of manual calculations and simulation using PVSyst software.

4.2.1. Basic calculations' results

4.2.1.1. PV array

Minimum number of PV modules was calculated to satisfy the design requirements. PV modules of polycrystalline silicon type (or equivalent) of (270 WP) as peak power were selected (I_{sc} = 9A, V_{oc} = 37.7 V, I_m = 8.45A, V_m = 31.84 V) at standard test conditions STC. Total watt peak of PV modules was calculated using Eq. (3). PSSH in Egypt was taken as 7 h, the efficiency of batteries as well as thermal efficiency of PV modules were assumed to be as 85%. So, total peak power was calculated as 8,996.54 WP. By substitution in Eq. (4), minimum number of PV modules were determined as 40 modules. The PV array of the system consisted of 2 PV modules in series and had to be organized in sub-arrays of

Table 3
Factors corresponding to lowest average temperature

Temperature (°F)	Temperature (°C)	Factor
80	26.7	1.00
70	21.1	1.04
60	15.6	1.11
50	10.0	1.19
40	4.4	1.30
30	–1.1	1.40
20	–6.7	1.59

Table 4
Output parameters from wave software

Parameter	Value
Feed flow, m^3/d	14.96
Concentrate flow, m^3/d	11.97
Feed pressure, bar	58.26
Average flux, LMH (L/m^2/h)	24.150
Permeate TDS, mg/L	435
Total active area, m^2	5.2
Specific energy consumption, kWh/m^3	10.16

20 parallel strings, therefore the total array peak power of the system was (8.45 × 31.84) × (2 × 20) = 10.8 KWP, which covered the amount of energy required.

4.2.1.2. Battery bank

Since the RO unit needs a stable power supply, the number of batteries storage were calculated. Days of autonomy were assumed to be 1.5 d, MDOD was taken as 60%, batteries ampere, and voltage were assumed to be 160 Ah and 12 V. By substitution in Eq. (5), the number of batteries were determined as 64. Battery set consisted of 4 batteries in series and 16 batteries in parallel, therefore, the battery set was rated as (48 V/2,560 Ah). It would give a total power of 122,880 W which was enough to power the plant for nearly 3 d and 3 h continuously.

4.2.1.3. Solar charge controller

The size of the solar charge regulator was determined based on selected PV module specifications using Eq. (6). It should be rated as 247 A at 48 V or greater. Four solar charge controllers each one was rated as (80 A at 48 V) had been selected. It would be connected in series (personal communication).

4.2.2. Simulation results

Fig. 5 shows the designed stand-alone system's main parameters and main results from the simulation.

Fig. 6 shows the performance ratio which is a very important value to evaluate the quality of selected photovoltaic module. Fig. 7 shows monthly values of the relation between solar radiation and ambient temperature. The main results from the simulation are presented in Fig. 8.

The solar irradiation and the ambient temperature had a significant influence on the performance of the PV system. As irradiation increases, the PV current increases significantly due to high energy absorbed by the PV modules (Fig. 9).

4.3. Wind turbine

4.3.1. Battery bank

Also, calculations for wind turbine design have been done in order to satisfy the total watt-hours for operation. Assumptions mentioned in the previous chapter were taken into considerations. By substitution in Eqs. (7)–(9) and by assuming that all batteries were connected in parallel with 12 V, the total number of batteries were determined as 74 rated as (160 Ah, 12 V). It would give a total power of 142,080 W which was enough to power the plant for nearly 3 d and 15 h continuously.

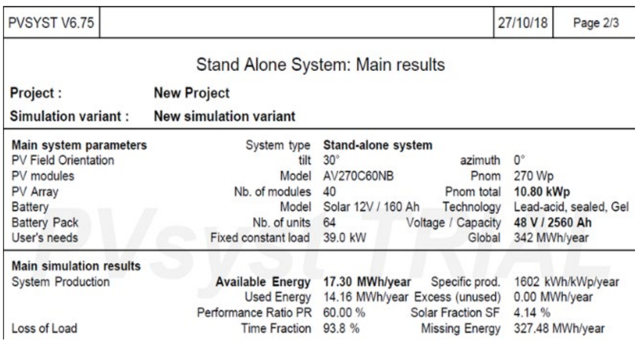
4.3.2. Wind turbine total power

By using Eq. (10), power required from wind turbines was determined as 3.25 kW. Commercial wind turbine which gives power equal to 5 kW will be used.

5. Cost analysis

In this section, a cost of the proposed plant had been calculated. The rate of purchasing one kWh of electricity monthly from the grid and producing it through off-grid systems "whether solar energy or wind energy as power sources" had been analyzed and discussed. Several references were used to collect the following relative prices data [24–30].

The cost per cubic meter of the produced fresh seawater was calculated using the results in Table 5. It was found from the results that the cost of cubic meter in the case of wind–RO plant was lower than PV–RO plant by about 0.02 $\$/m^3$.



PVSYST V6.75		27/10/18	Page 2/3

Stand Alone System: Main results

Project : **New Project**
Simulation variant : **New simulation variant**

Main system parameters	System type	**Stand-alone system**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	AV270C60NB	Pnom	270 Wp
PV Array	Nb. of modules	40	Pnom total	**10.80 kWp**
Battery	Model	Solar 12V / 160 Ah	Technology	Lead-acid, sealed, Gel
Battery Pack	Nb. of units	64	Voltage / Capacity	**48 V / 2560 Ah**
User's needs	Fixed constant load	39.0 kW	Global	342 MWh/year
Main simulation results				
System Production	**Available Energy**	**17.30 MWh/year**	Specific prod.	1602 kWh/kWp/year
	Used Energy	14.16 MWh/year	Excess (unused)	0.00 MWh/year
	Performance Ratio PR	60.00 %	Solar Fraction SF	4.14 %
Loss of Load	Time Fraction	93.8 %	Missing Energy	327.48 MWh/year

Fig. 5. Main results from PVSyst.

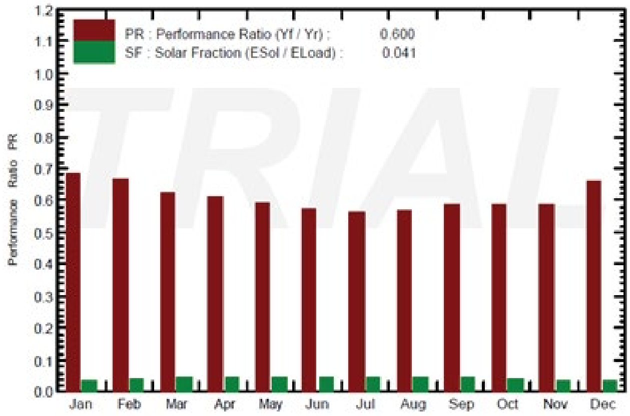


Fig. 6. Performance ratio and solar fraction (monthly values).

	GlobHor	T Amb
	kWh/m²	°C
January	90.2	13.65
February	106.5	13.89
March	163.4	16.03
April	195.3	17.97
May	223.9	20.78
June	235.1	23.63
July	240.8	26.37
August	221.9	26.82
September	183.2	25.25
October	143.3	22.84
November	101.0	18.74
December	83.9	15.31
Year	1988.4	20.15

Legends: GlobHor Horizontal global irradiation
T Amb Ambient Temperature

Fig. 7. Variations of solar radiation with ambient temperature (monthly values).

	GlobHor kWh/m²	GlobEff kWh/m²	E Avail MWh	EUnused MWh	E Miss MWh	E User MWh	E Load MWh	SolFrac
January	90.2	126.1	1.027	0.000	28.06	0.954	29.02	0.033
February	106.5	134.9	1.097	0.000	25.22	0.989	26.21	0.038
March	163.4	187.7	1.531	0.000	27.72	1.297	29.02	0.045
April	195.3	198.2	1.616	0.000	26.73	1.347	28.08	0.048
May	223.9	204.3	1.664	0.000	27.67	1.348	29.02	0.046
June	235.1	203.6	1.659	0.000	26.78	1.296	28.08	0.046
July	240.8	212.3	1.730	0.000	27.68	1.336	29.02	0.046
August	221.9	215.3	1.756	0.000	27.66	1.355	29.02	0.047
September	183.2	200.9	1.636	0.000	26.78	1.299	28.08	0.046
October	143.3	177.8	1.450	0.000	27.87	1.148	29.02	0.040
November	101.0	140.9	1.151	0.000	27.17	0.909	28.08	0.032
December	83.9	120.5	0.979	0.000	28.14	0.879	29.02	0.030
Year	1988.4	2122.5	17.297	0.000	327.48	14.156	341.64	0.041

Legends:
GlobHor Horizontal global irradiation
GlobEff Effective Global, corr. for IAM and shadings
E Avail Available Solar Energy
EUnused Unused energy (full battery) loss
E Miss Missing energy
E User Energy supplied to the user
E Load Energy need of the user (Load)
SolFrac Solar fraction (EUsed / ELoad)

Fig. 8. Balances and main results.

	GlobHor kWh/m²	IArray Ah	EArrNom kWh
January	90.2	21306.6	1358
February	106.5	22794.6	1452
March	163.4	31747.3	2021
April	195.3	33518.0	2135
May	223.9	34546.8	2200
June	235.1	34429.1	2192
July	240.8	35887.5	2286
August	221.9	36371.7	2318
September	183.2	33931.4	2164
October	143.3	30079.1	1915
November	101.0	23839.0	1517
December	83.9	20366.4	1297
Year	1988.4	358817.5	22854

Legends:
GlobHor Horizontal global irradiation
IArray Array Current
EArrNom Array nominal energy (at STC effic.)

Fig. 9. Effect of irradiation on the power output.

5.1. Monthly electricity prices

There were some parameters taken into considerations when calculating monthly kWh price such as:

- Plant lifetime was assumed to be 20 y.
- As calculated before, the plant monthly demand was considered as 1,209 kWh and results from Table 5 were used.

To evaluate the feasibility of the proposed system, Table 6 shows that the proposed off-grid system produces monthly kWh at a rate higher than the purchased from the government by 3 and 5 Pt/kWh in case of wind energy and solar energy, respectively. However, considering the increase in electricity prices in Egypt, Fig. 10 through the upcoming 20 y [30]. Results indicate that the proposed off-grid system is a cost-effective. Moreover, selecting a location far away from the grid to be the location of the plant

Table 5
Total plant cost

Plant	Price (USD)
PV-RO	$23,980
Wind-RO	$23,580

Table 6
Off and on grid monthly kWh price comparison

Power source	Piasters per kWh (in 2019)	Piasters per kWh (after 10 y for example)
On grid	140 [24]	158 [30]
Wind energy	143	143
Solar energy	145	145

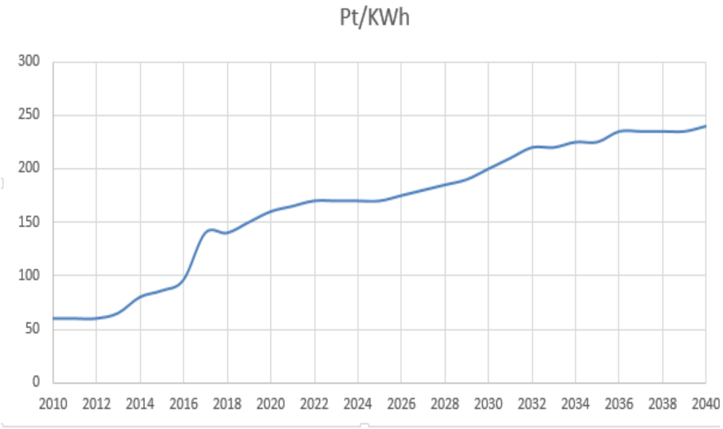


Fig. 10. Increasing commercial electricity prices in Egypt (more than 1,000 kWh monthly).

will ensure lower producing kWh prices compared to the purchased one from the government.

6. Conclusions and future work

6.1. Conclusions

From the study of the proposed water desalination system, it can be concluded that:

- Using renewable energy systems in water desalination is a promising solution to solve the lack of freshwater in remote areas in Egypt.
- The performance of the system depends on the technology selected for the desalination unit components.
- The computer program which was used in this study can be applied to any site with different weather conditions.
- The proposed wind-RO system has a lower total cost than PV-RO system as well as it has a lower rate for the produced KWH per month.
- Further research is needed in testing renewable energy systems in different areas in Egypt.

6.2. Future work

- Enlarging the capacity of the proposed system can be studied to enhance the cost of KWh produced per month.
- Energy recovery device can be added to this design for better efficiency.
- Hybrid PV-WIND-RO can be applied to the same RO unit [14,23].

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