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Feasibility study of grid-connected photovoltaic system for seawater desalination station in Algeria

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ABSTRACT

This study expounds how a reverse osmosis desalination system coupled to a photovoltaic system connected to the grid (hybrid PV-Grid) can be a sustainable option in satisfying the increasing fresh water demand in Algeria and worldwide. A feasibility analysis of the technical, economic and environmental potential of the grid-connected photovoltaic (PV) energy system to electrify seawater desalination station in Algeria is investigated. A seawater reverse osmosis (SWRO) desalination station of Zeralda (Algiers) is selected as a case study. The assessment criteria for our study comprised net present cost (NPC), cost of energy (COE) and energy balance criteria (EB). Moreover, sensitivity analyses of the global solar radiation, the interest rate, the PV capital multiplier and the PV module efficiency parameter on the optimal hybrid energy system configuration were carried out. The results demonstrate that the hybrid grid-connected PV system has the potential to supply a significant power for seawater desalination station with COE of 0.102 $/kWh. Moreover, the PV production of the optimal hybrid configuration has resulted in 67% of renewable fraction (RF), and an annual reduction of 34.9 tons in the CO_2 emissions.

Keywords: Grid-connected photovoltaic; Feasibility; Reverse osmosis; Hybrid system; Desalination

1. Introduction

Water's strategic and vital dimensions demand a policy of maximum mobilization and rational exploitation of this resource. This area poses security and economic challenges to any country. Water security closely relates to economic, health and ecological security, while affecting food security in particular. Nevertheless, population growth and climatic variability are driving an increase in nonconventional sources of water such as desalination of seawater or brackish water [1]. Desalination, having proved to be an advantageous, viable technology for supplying drinking water [2], now plays a key role in controlling regional water challenges [3,4]. Desalination technologies are mainly classified based on their processes: thermal, membrane and hybrid. Thermal desalination employs heat to separate water from a saline feed. The most common thermal desalination systems are: multi-stage flash (MSF), multiple-effect distillation (MED), multi-effect boiling (MEB), thermal vapor compression (TVC) and mechanical vapor compression (MVC). Membrane desalination employs electrical high-pressure pumps feeding semi-permeable membranes that separate water from the saline feed. The main membrane desalination processes are: reverse osmosis (RO), forward osmosis (FO), electro-dialysis (ED) and membrane distillation (MD). Furthermore, several new desalination technologies have been developed, including air dehydration, ion exchange and dew vaporization.

Currently, desalination systems have been transitioning from thermal-based to membrane-based technologies [5]. Reverse osmosis (RO), as both seawater reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO), is now the most widespread of all desalination processes because of its high energy efficiency and technological enhancements [6]. As per the International Desalination Association's recent statistics, RO represents 65% of all installed desalination plants [7].

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Globally, an estimated of 90 million m^3 of water is desalinated per day by around 18,500 desalination plants [8]. With regard to Algeria, according to recent demographic data, the population is expected to double in the next thirty years, while water resources will remain the same [9]. On average, the country receives 100 billion m^3 of rain per annum, of which 85% evaporates. The remaining 15% runs on the surface to rivers and the sea, or infiltrates into the subsurface layers [10]. According to the Ministry of Water Resources, water resources in Algeria consist of 10 billion m^3 in the northern regions (of which 74% is surface water and 26% is underground water), and 5.37 billion m^3 in the Saharan regions (of which 6.89% is surface water and 93.1% is underground water) [11]. With these limited resources and an imminent crisis in the supply of potable water, Algeria is classified as a water-scarce nation. It is ranked sixth among countries suffering most severely from water shortages, and it will jump to fourth place by the year 2025 if no reliable plan is adopted [12].

Seawater desalination has been considered a sustainable solution for Algeria, a country which has 1,200 km of coastline along the Mediterranean Sea [13]. The Algerian experience of desalination is intimately related to the development of the oil and steel industries [9]. In 1964 (just two years after independence), Algeria's first desalination plant was built to meet the needs of the petrochemical facility of Arzew in western Algeria [13]. Since then several other desalination units have been put into operation, to fulfill the needs of huge electrical power plants. There are furthermore some small-scale units, which are used primarily to produce water for human consumption in Saharan petroleum and gas bases [9].

There are already 56 desalination plants in operation, with a combined capacity of about 146,000 m^3 per day [13]. Reverse osmosis (RO) based technology is used in 22 of these plants, and produces more than 60% of the total capacity [13]. However, forecasts suggest that water scarcity will become more severe [14]. Population growth, high irrigation water demand, and overuse of groundwater have led to a need for increased desalination activities in the region. In order to resolve this problematic situation, a new desalination program has been launched. This program was executed as a joint project by the Algerian Energy Company and the Algerian Water Authority. Sixteen mega-plants with capacities ranging from 100,000 to 500,000 m^3 per day are now in operation. All these plants are based on RO [15].

Drinking water treatment and supply are energy intensive activities; approximately 7 % of electricity generated globally is consumed in the production and distribution of potable water and in wastewater treatment [16]. The energy requirements of water treatment and supply processes depend upon factors including the contamination of the water, water quality, geographical conditions, and the age of the infrastructure and technology [17]. The desalination process requires more energy than conventional water treatment processes [18–20]. Conventionally powered desalination is also an unsustainable process because of the need for fossil fuels to supply the high energy demand of freshwater recovery [6]. Desalination processes emit approximately 76 million tonnes of CO_2 per year [8], which means shifting towards sustainable desalination is now an inevitable challenge. This has given important market potential to renewable energy-powered desalination systems worldwide [21]. Yet, only 1% of all desalinated water is produced from renewable energy sources [21]. Of all renewable energy sources, solar energy-driven desalination systems have been the most carefully investigated, including the MD processes driven by thermal solar energy [22–24], the ED driven by PV [25–27], and the FO driven by solar energy [28–30]. Nevertheless, among these processes, the RO is the most studied because this technology is more energy efficient [31] than nano-filtration [32] and electro dialysis [32,33]. Koroneos et al. [34] presented an integrated model by comparing several desalination systems based on renewable energy sources for a particular case study. They found that the renewable source potential has a high influence on the cost of the electricity and the water production cost. Davies and Hossain [35], investigated the integration of RO with solar PV to cover the water demands for irrigation and cooling of a greenhouse. The results were compared to theoretical predictions to obtain conclusions about energy usage, sizing and cost of the overall system. Went et al. [36] investigated the energy demand of small PV-RO systems with different energy recovery devices. The results show that the best performance was achieved by the pressure exchanger. Poovanaesvaran et al. [37], reviewed the design features of a small scale photovoltaic powered brackish water reverse osmosis system (PV-BWRO) such as cost, energy, design configuration, energy recovery devices, etc. Hossam-eldin et al. [38] investigated the integration of hybrid renewable energy systems in RO desalination by using a mathematical model to find the best energy system configuration with the best water production cost. Bilton et al. [39] presented an economic approach to optimally design small-scale RO systems powered by several electrical power systems composed of photovoltaics, wind turbines, diesel generators, batteries, and hybrid systems. It has been found that the local climatic conditions strongly impacted the economic potential of different technologies. Janghorban Esfahan and Yoo [40] proposed an extended pinch analysis approach (FWaPA) combined with the multi-objective genetic algorithm to find the optimal size of PV panels, membranes, and capacity of water storage tanks. Three objective functions are considered: the required produced potable water during the first year of operation, the produced potable water during a normal operation year, and the total annual cost of the system. The results showed the efficiency of the proposed approach for retrofitting the off-grid batteryless (PV-RO) system with a water storage tank. Kim et al. [41] studied the dynamic analysis of coupling an RO plant with hybrid energy systems under variable operating conditions. The approach is tested on various case studies and the results showed that the dynamic optimization of the electrical energy excess add an operational flexibility in the energy management at the utility scale. Gökçek [42] evaluated the operations of seven different (off-grid) power systems (wind-photovoltaic-diesel-battery) used to satisfy the electrical energy demand of a small-scale reverse osmosis system with a capacity of 1 m^3/h used on Bozcaada Island, Turkey. The results showed that combining the hybrid power system and RO system could be a cost-effective method for remote areas with good wind and solar power potential.

Although PV-powered RO (PVRO) is the most used, it has not been considered a cost-competitive solution when compared with conventional desalination powered by fossil fuels [6]. However, the rapid use of photovoltaic systems has led to a decrease in the unit cost of electricity production over the last years [43]. PV-RO large plants with production capacities over 30,000 m^3/day was planned for installation in United Arab Emirates and Saudi Arabia [44]. Therefore, RO desalination systems powered by photovoltaics are promising technologies for desalination of seawater and brackish water. These systems can be designed according to the drinking water needs and renewable energy resources potential.

Summing up, there is much research into the integration of renewable energies into RO plants in off-grid (standalone) mode, however, only a few studies have considered the grid-connected mode. Moser et al. [45], presented a comparison between several renewable energy options to power RO and MED desalination plants. Two methods were applied for a specific case study within the MENA region; the first method suggested grid compensation and the second suggested the addition of an equivalent firm power supply capacity to cover the energy shortage. Ko et al. [46] proposed a novel approach of a grid-connected SWRO plant based on energy cost reduction. In this context, this paper analyses the feasibility of using a grid-connected photovoltaic hybrid system for a seawater desalination unit based on the electric feed-in tariff rate of Algeria and assesses the technical, economic and environmental viability of the system. The desalination station is located in Zeralda, Algiers (36°43′N, 2°53′E), the station provides 2,500 m^3/d of drinking water from sea water. The excess of photovoltaic energy production is sold to the utility grid.

2. Methodology

The aim of this paper is the proposition of electricity production from grid-connected photovoltaic (PV) system to power 2,500 m^3/d seawater RO desalination plant. The proposed PV-grid-SWRO system contains a PV generation subunit and a RO subunit as depicted in Fig. 1. The RO subunit comprises of a pump, membrane, and storage tank. The PV generation subunit consist of three key components: 1) a PV array as a power generator, 2) an electrical grid to cover electricity shortage of the system and purchase electricity surplus of the system, and 3) an inverter to manage electricity transportation to and from the grid. The research methodology includes three principal phases: Research data were gathered in the first phase such as determining the local meteorological resources, estimating the electrical demand for the RO unit, the second phase included the modelling of the PV generation subsystem using the HOMER software based on input parameters (technical and economic parameters of the system components, load profile, meteorological data, and constraints parameters). In the third phase the energy balance criteria (EB), the net present cost (NPC) and levelized cost of energy (COE) are considered as design criteria to assess the techno-economic feasibility of the proposed power generation system.

Our objective is to find an optimal configuration of grid connected PV system that satisfy the annual EBC [Eq. (1)] with the lowest NPC [Eq. (2)] and COE [Eq. (4)]

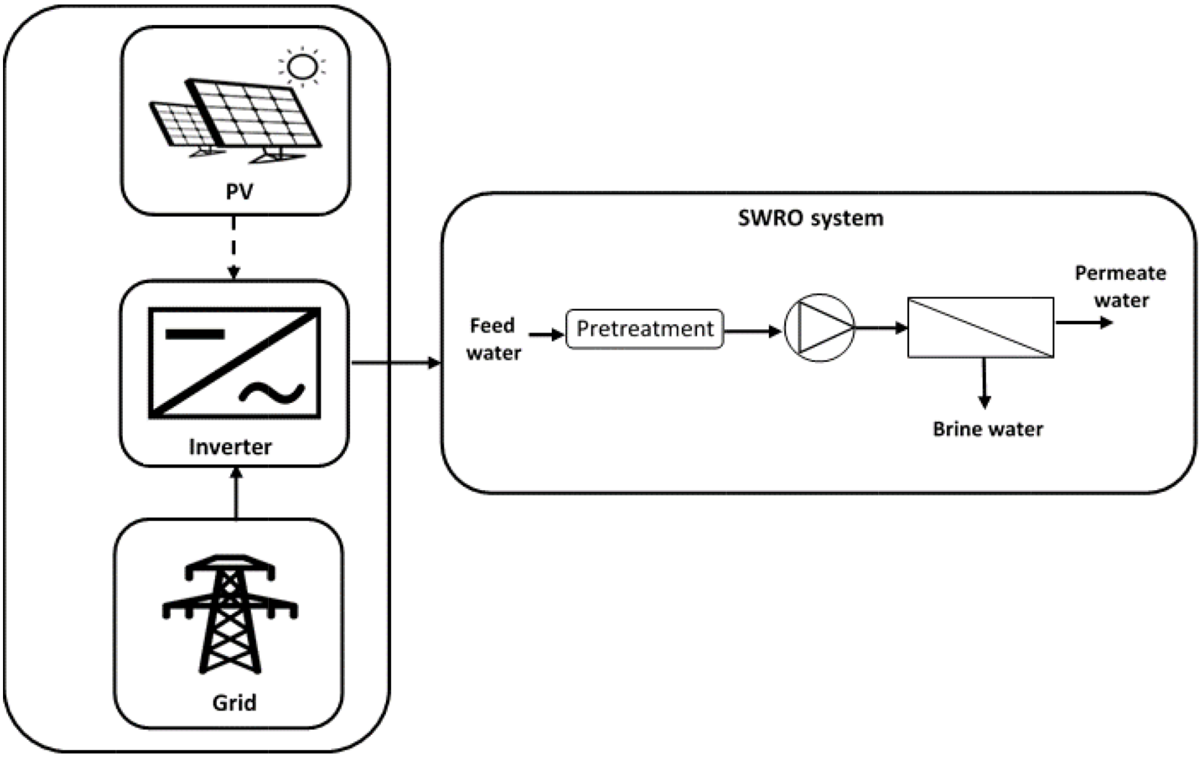

Fig. 1. PV-Grid-SWRO system components.

$$E_{sold} > E_{purchased} \tag{1}$$

where E_{sold} is the amount of photovoltaic energy sold to the grid and $E_{purchased}$ is the amount of electricity purchased by the system from the grid.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \tag{2}$$

where $C_{ann,tot}$ is the total annualized cost, i the annual real interest rate (the discount rate), R_{proj} the project lifetime, and CRF is the capital recovery factor, given by the following equation:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where i is the annual real interest rate and N is the number of years.

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{4}$$

where $C_{ann,tot}$ is the total annualized cost, E_{prim} is the total amount of primary load serves per year, E_{def} is the total amount of deferrable load serves per year and $E_{grid,sales}$ is the amount of energy sold to the grid per year.

3. Case study

3.1. Site presentation

The desalination station is located in Zeralda which is a suburb of Algiers in northern Algeria. It is located 29-km west of Algiers Centre, Latitude: 36°44′ N Longitude: 2°50′ E. It is agricultural and tourist vocation since it has 5 km of beach. The seawater desalination station has been operational since 2008. Fig. 2 illustrates the geographical location of the case study.

3.2. Meteorological data

The performance of the PV module is related to the meteorological characteristics of the site (solar irradiation and ambient temperature). The hourly solar radiation data and the clearness index of the site, the data was obtained from the NASA Surface Meteorology and Solar Energy (SSE) database [47]. The annual average of the solar radiation is estimated to be 4.51 kWh/m^2/d, with a clearness index of 0.55. This solar potential is important and it can be exploitable for electrification. The other set of meteorological data is the hourly temperature data which is imported from Meteonorm 6.0. The annual average temperature is 17.7°C. The average monthly solar radiation and temperature data are illustrated in Fig. 3.

3.3. Load profile

The sizing of a PV system depends mainly on the load consumption. In our case, it is the energy required to drive the desalination unit operating by reverse osmosis technique (RO), some assumptions are made to estimate the energy demand: the desalination station is assumed to work with its maximum capacity for 24 h which is 2500 m^3/d, with salinity of 38.4 g/L. The specific energy required for desalination is 2.5 kWh/m^3 [48]. The average base load for our system is 261 kWh. In order to make energy demands more realistic, 5% noise is added in the model for daily and

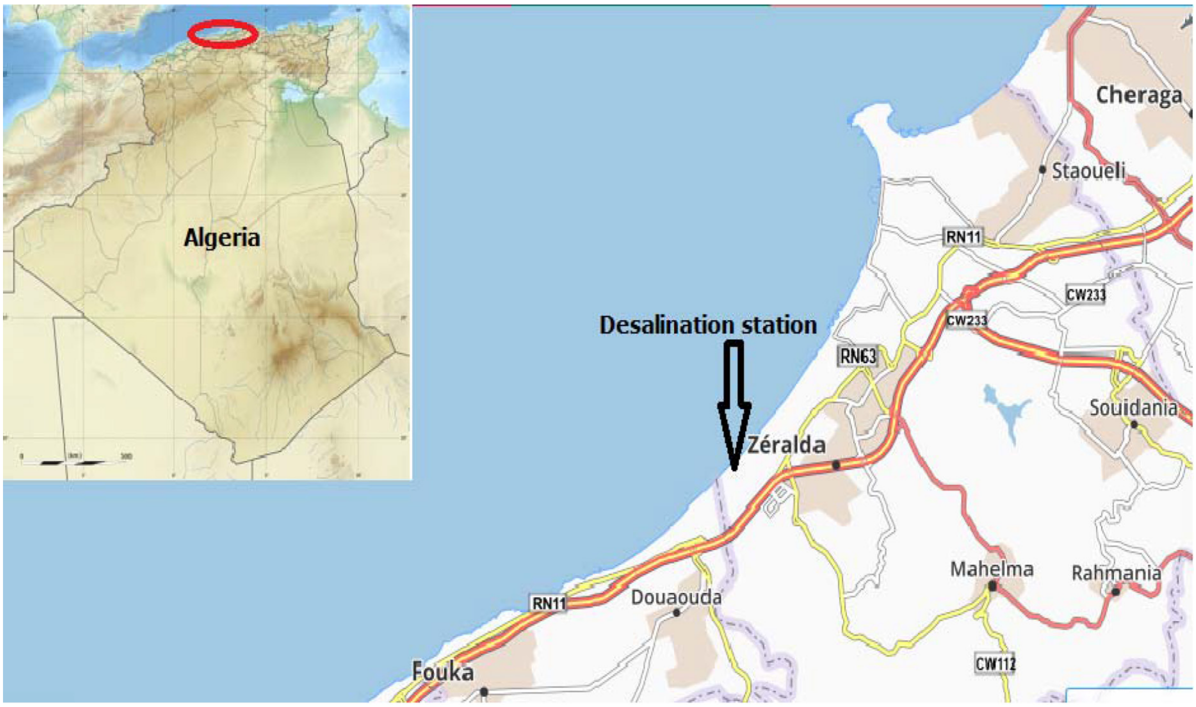

Fig. 2. Geographical location of the desalination unit.

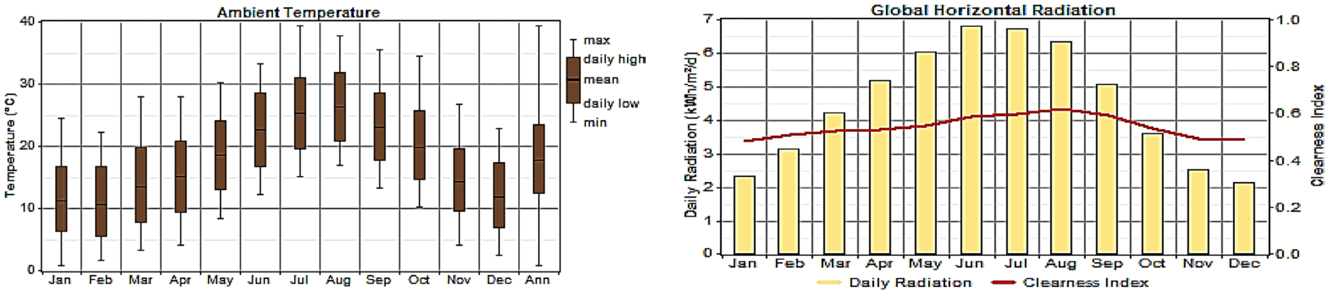

Fig. 3. Meteorological characteristics of the site.

hourly random loads variation, with an average daily output of 6247 kWh/d.

3.4. System components

As shown in Fig. 4, our system is grid-connected PV system, it consists of PV modules, inverter, grid and the load. The electricity is generated by the PV modules and the electricity surplus is sold to the grid by following the feed in tariff scheme. The grid functions as a backup electricity supplier to the load when energy generated by the PV is insufficient.

Simulation and analysis of the system are performed by inserting resources data, economic constraints, control methods, and inputs on component types, their numbers, costs, efficiency, longevity, etc. Description of these components is given in the following section:

- PV array: PV module (CEM285P-72) made in Algeria by Condor company is used in this study. The cost of PV module is (30010.50 DA) [49]. Taking on consideration the installation and transportation costs, in this study the capital cost of the PV module is $350. The operating and maintenance cost is estimated at $20, the replacement cost is specified as zero, lifetime is 25 years, no tracking system, and the effect of temperature is considered. Table 1 summarized the technical characteristics of the PV module [50].
- Bidirectional Converter: The capital cost of the converter is $0.4/W, the replacement cost is $0.2/W, the operating and maintenance cost is $3/y, lifetime is 15 y, and the efficiency is 90% as a rectifier and 92% as an inverter.

In 2014, Algeria introduced feed-in tariff (FIT) scheme for the solar PV installations to support and speed up the achieving of the Algerian Renewable Energy and Energy Efficiency Development Plan. The tariff is differentiated according to the size of the PV plant; plants with a capacity

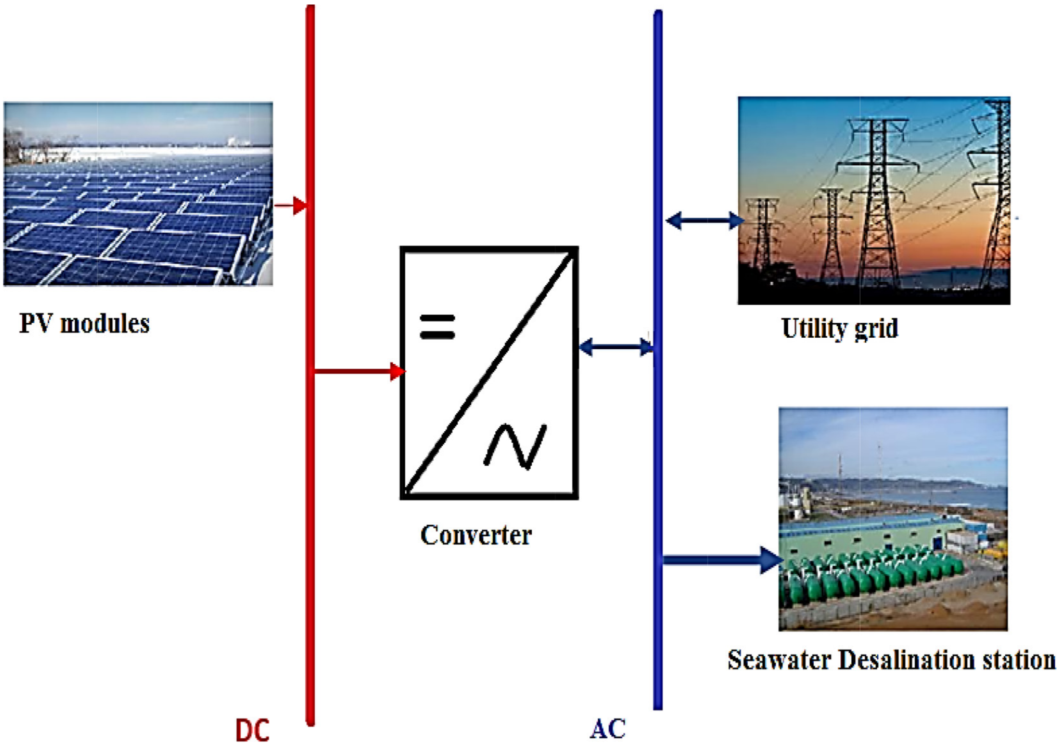

Fig. 4. The basic schematic of the seawater desalination station grid connected PV system.

Table 1
CEM285P-72 module technical characteristics

Technical characteristics	Value
Dimensions	1956 mm × 992 mm × 50 mm
PV module rated power	285 W_p
Maximum voltage	44.6 V
Maximum current	8.3 A
Open circuit voltage	36 V
Short circuit voltage	7.92 A
NOCT	45 + 2°C
Efficiency	13 %

equivalent or larger than 1 MW can benefit from the FIT. In our case, Renewable electricity sellback tariff is 15.94 DA/kWh (0.14 $/kWh) and the grid tariff is 1.36 DA/kWh (0.01 $/kWh).

3. Results and discussion

3.1. Simulation results

The system is simulated to find the optimal system with the amount of PV energy injected into the grid greater than the amount of electricity purchased by the system from the grid. There are several feasible solutions for our system, but we chose to analyze the technical, economic and environmental results of the optimal solution that satisfy our constraints which is (2.2 MW PV, 1 MW converter), Table 2 summarizes the different results of the optimal solution.

We note that a total satisfaction (100%) of the primary charge is obtained with an amount of 11.4 % excess electricity. The annual net purchases of the system are –55.22 MW/year, this negative value means that the annual energy sold to the grid (1,527.39 MWh/year) is more than the annual energy purchased from the grid (1,472.17 MWh/year) which represents 33% of the total electricity production. Furthermore, the annual PV production of the system is 3,054.32 MWh (67% of the total electricity production) from which 1,526.92 MWh (50%) of the PV production is supplied to the desalination unit; this percentage can be explained by the fact that electricity demand of desalination unit is important outside the favorable hours of PV subsystem.

The initial capital cost of the optimal system was 3,101,755 $, of which the PV modules cost is the dominant cost with 87.1% and the inverter cost represents 12.89% of the initial capital cost. The NPC of the optimal grid-connected PV system is 2,665,020 $ and the COE is 0.102 $/kWh. The income obtained from selling electricity to the grid is estimated at –199,114 $/year which is more than the money spent to buy electricity from grid, this cost influences positively on the operating cost of the system which is estimated at –41,728 $/year, the negative cost means that the hybrid system retrieves an annual income of 41,728 $ as illustrated in cash flow summary in Fig. 5. Another advantage of the grid-connected photovoltaic system was CO_2 footprint reduction of –34,900 kg/year.

Table 2
Technical, economic and GHG emissions of the optimal system

Technical	
PV array (MW)	2.2
Converter (MW)	1
PV production (kWh/year)	3,054,323 (67%)
Grid purchases (kWh/year)	1,472,176 (33%)
Grid sales (kWh/year)	1,527,396
Excess of electricity (%)	11.4
Economic	
NPC ($)	2,665,020
COE ($/kWh)	0.102
Capital cost ($)	3,101,755
Replacement cost ($)	83,453
O&M cost ($)	–478,614
Salvage ($)	–41,574
GHG emissions (kg/year)	
Carbon dioxide	–34,900
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	–151
Nitrogen oxides	–74

3.2. Sensitivity analysis

In this section, a four-dimensional sensitivity analysis was performed to study the impact of different sensitivity input variables and their variations on the system outcomes. The variables are: the global solar radiation, the interest rate, the PV capital multiplier and the PV module efficiency parameter. The spider graph is used to determine and depict the sensitivity of the system outputs to each variable.

As shown in Figs. 6, 7 and 8, the global solar radiation (GSR) intensity line is the steepest line in all the graphs (the cost of energy (COE), the PV production and the grid sales) which means that the system performance is most sensitive to the GSR intensity. The COE of the sys-

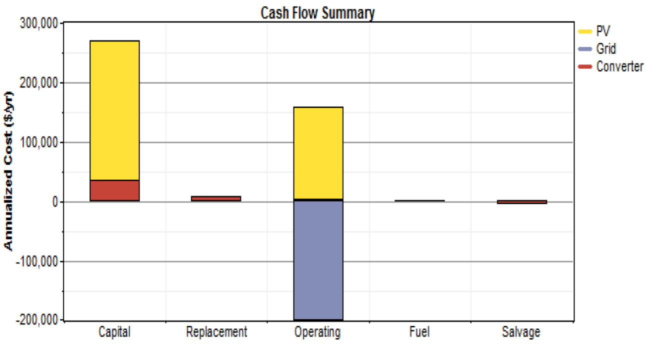

Fig. 5. Cash flow summary of the system.

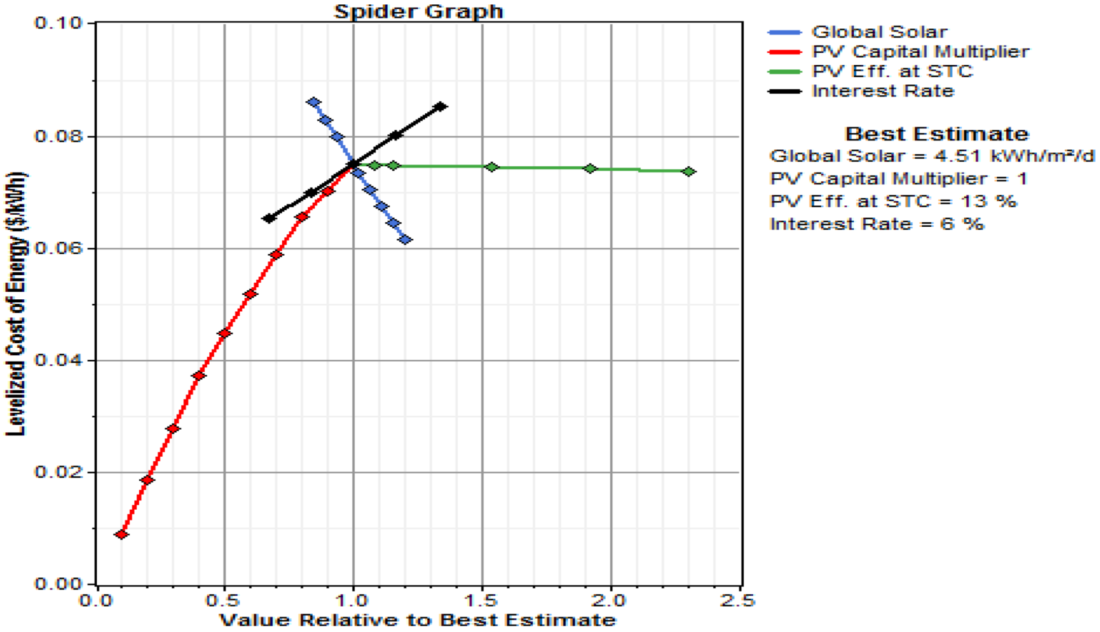

Fig. 6. Effect of parameters variations on the COE.

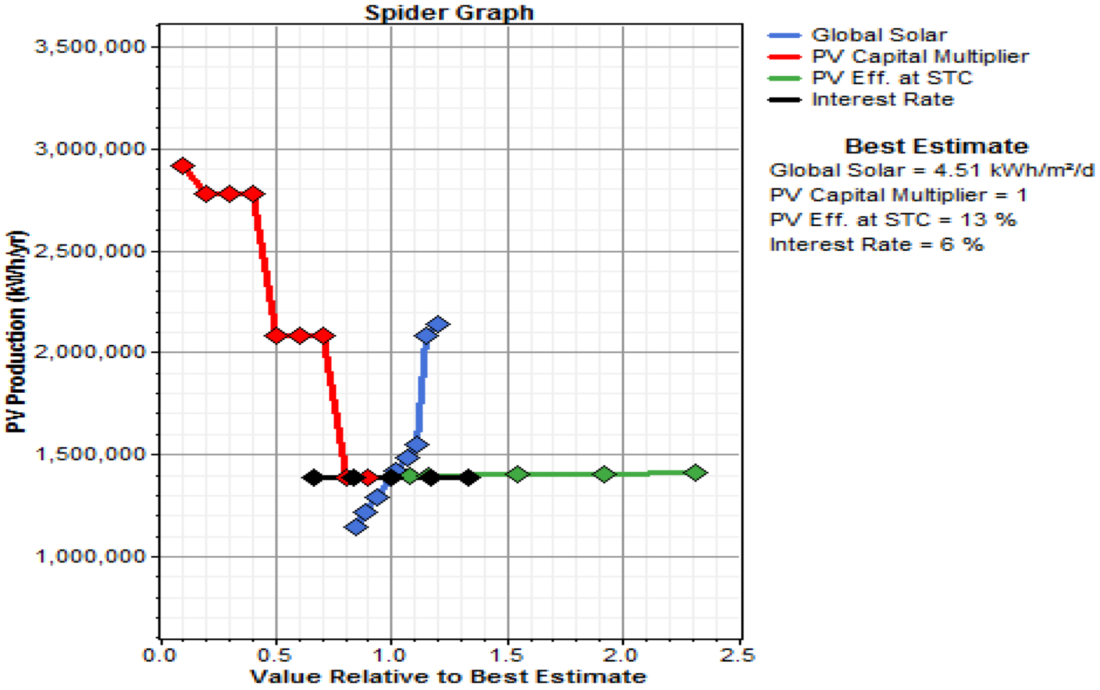

Fig. 7. Effect of parameters variations on the PV production.

tem decreased from 0.086 $/kWh to 0.062 $/kWh when the global solar radiation increased from 3.8 kWh/m^2/d to 5.4 kWh/m^2/d. The increase in the GSR intensity uniformly leads to a decrease in the net present cost of the system (NPC) and an increase of the renewable fraction. The PV production and the grid sales are also most sensitive to the GSR intensity; they are linearly related to the GSR intensity. The PV production of the system increased from 1,143.997 MWh to 2,133.242 MWh and the grid sales increased from 292.639 MWh to 1,050.553 MWh when the global solar radiation increased from 3.8 kWh/m^2/d to 5.4 kWh/m^2/d; for an increase of 1.6 kWh/m^2/d, an increase of 186% in PV production and 358% in grid sales have been observed also.

Furthermore, the interest rate has also a strong influence on the COE of the system. As depicted in Fig. 9, the COE and real interest rate are linearly related; when the real interest rate varied from 4% to 8%, the COE increased from 0.065 $/kWh to 0.085 $/kWh, as can be explained by Eq. (4): the total annualized cost of the system $C_{ann,tot}$ increases when

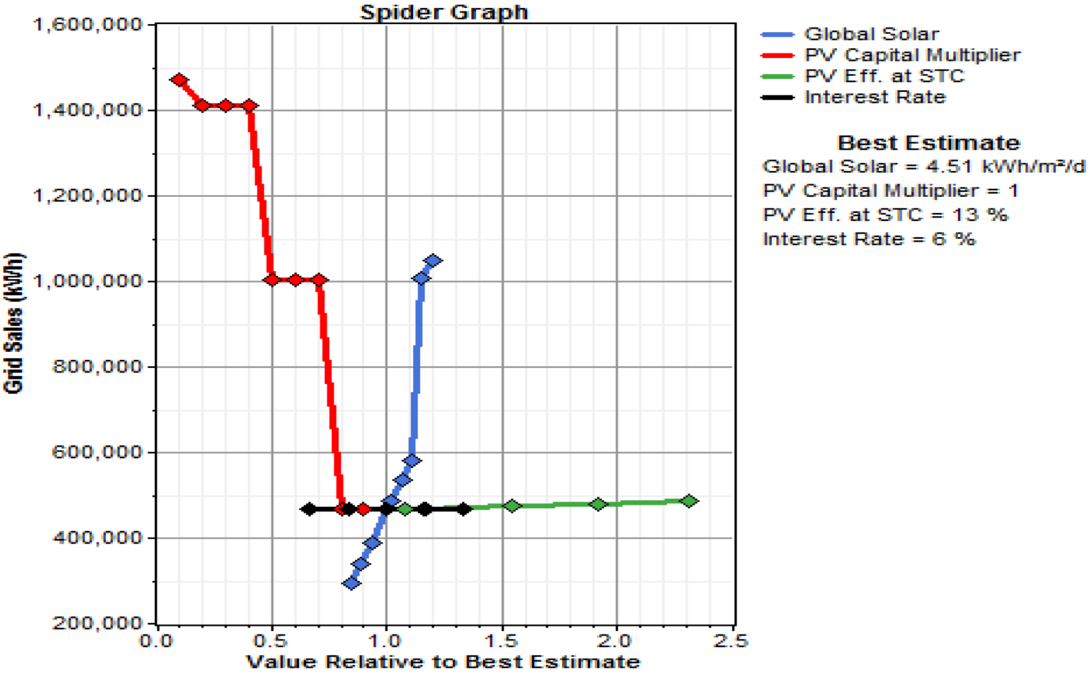

Fig. 8. Effect of parameters variations on the grid sales.

the real interest rate increases also. Unlike the COE, the net present cost (NPC) of the system is inversely related to the real interest rate according to Eq. (2) and as shown in Fig. 9. However, the interest rate has no impact on PV production and grid sales.

As for the PV capital multiplier variable, this factor is used to model a scenario where the PV capital cost is more or less than the actual PV capital cost, and it can be seen from Fig. 6 that this factor is inversely related to the COE of the system. The COE was three times smaller with a PV capital multiplier of 0.2 vs. a factor of 0.8, meaning that a cost reduction of the PV technology will lead to a significant decrease in the overall cost of the system.

As shown in Fig. 6 the variation of the PV module efficiency from 13% to 28% revealed a decreasing margin of only 1.1% in the COE value and this can therefore be considered as negligible compared to the other sensitivity variables. It can be seen from Figs. 7 and 8 that the PV subsystem production and grid sales are linearly related to the PV module efficiency. The PV production of the system increased from 1,388.326 MWh to 1409.726 MWh and the grid sales increased from 466.771 MWh to 485.211 MWh, as

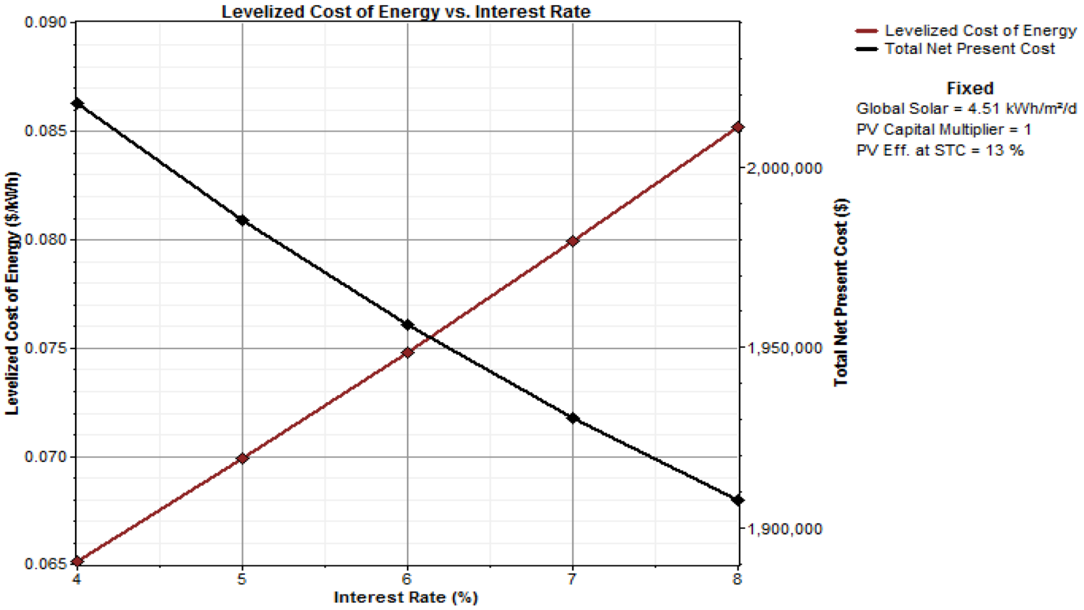

Fig. 9. Sensitivity of the NPC and COE to variations in the interest rate.

can be seen, for an increase of 15% in the PV module efficiency, an increase of only 1.6 % of the PV production and the grid sales were observed. These results means that the PV module efficiency has a less direct impact on the overall system performance.

4. Conclusion

This study highlighted the feasibility of photovoltaic grid-connected system for the electrification of seawater desalination plant. The results showed the interest in the hybrid system as a key solution in to the electrification- generation process for a desalination plant in Algeria. The optimal configuration for the hybrid PV-grid-connected system provided 3,054.32 MWh/year PV production, which represents 67% of the renewable fraction. Furthermore, the system met 100% of the primary charge and returned to the grid more than the purchased electricity, with an annual income from the electricity sold to the grid estimated at to be $199,114/y.

A sensitivity analysis was also performed to investigate the impacts of the global solar radiation, the interest rate, the PV capital multiplier, and the PV module efficiency on the system's performance. The results indicated that the global solar radiation is the most influential variable on the cost of energy, PV production, and the grid sales. The second second-most influential parameter is the annual real interest rate. This has an important impact, particularly on the COE and NPC of the system. The PV capital multiplier and the PV module efficiency have a limited impact on the system performance compared to the global solar radiation and the interest rate.

To our knowledge, this study is the first to address the techno-economic benefits of considering a hybrid PV grid-connected system in the electrification process of seawater desalination plants in Algeria. It is evident that this choice is technically, economically, and environmentally applicable to small- and medium-sized seawater plants but remains problematic for large plants. However, with the support of significant public funds, the generalization of this approach will become a suitable and sustainable electrification option. Future studies will consider the coupling of SWRO desalination plants with other local renewable resources.

Acknowledgment

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Symbols

$C_{ann,tot}$ — Total annualized cost [$]
C_{NPC} — Net present cost [$]
COE — Levelized cost of energy [$/kW]
CRF — Capital recovery factor
E_{def} — Total amount of deferrable load serves per year [kW]
$E_{grid,sales}$ — Amount of energy sold to the grid per year [kW]
E_{prim} — Total amount of primary load serves per year [kW]
$E_{purchased}$ — Amount of electricity purchased by the system from the grid [kW]
E_{sold} — Amount of photovoltaic energy sold to the grid [kW]
i — Annual real interest rate
N — Number of years
R_{proj} — Project lifetime [year]

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