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OPTIMAL SIZING OF A HYBRID PHOTOVOLTAIC/WIND SYSTEM SUPPLYING A DESALINATION UNIT

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Abstract

This work presents the dimensioning of a wind-photovoltaic hybrid system for the supply of a seawater desalination plant (reverse osmosis desalination) located in Honaïne in the Tlemcen coastal region of Algeria. The plant has a production capacity of 200,000 m^3/day and supplies potable water for a population of about 555,000 people (the plant's energy demand is 1,825 MW). The main idea is to present a method for sizing and optimizing a hybrid system by introducing two scenarios: the first scenario treats the operation of the plant under good weather conditions. The second one introduces the notion of the worst month (poor weather conditions). For it, we developed a calculation code (Programming under the MATLAB environment) that allowed us to determine the size and optimization of the system, as well as the optimal technical and economic configuration (numbers of photovoltaic panels, wind turbines and batteries), as well as the total cost. The results obtained show on the one hand: the complementarity of the two scenarios, which allows a better reliability of the system, and this by using a number well defined of panels, wind turbines and batteries to ensure the long-term operation of the plant. On the other hand, the use of the hybrid system has allowed us to obtain a 51.46% benefit compared to fossil fuels, which gives the proposed study an important reliability, since it offers a very advantageous benefit in terms of cost and efficiency.

Keywords: Batteries, Cost, Desalination, Hybrid photovoltaic-wind system, Optimization technique.

1. Introduction

Algeria and other countries in the world are confronted with two major problems necessary for all developments: access to potable water and energy supply. The rational use of these two resources represents a major challenge, because the rapid

Nomenclatures

C_{bat}	Battery Capacity, Ah
C_{ff}	Total cost using fossil fuels, $
C_{kWh}	Price of 1 kWh of electricity, $
C_M	Maintenance cost, $
C_p	Wind turbine coefficient of performance
C_{RE}	Total cost using renewable energy, $
E_d	The desalination plant energy, MW
E_{PV}	Photovoltaic energy, kWh
E_w	Wind energy, kWh
f	Permeability
H	Solar irradiation , W/m^2
I_{MP}	Current at Maximum Power, A
N_d	The deficit days
N_m	Number of days of the worst month
N_{Tot}	Total number of operating days (365 days).
R_{PV}	Photovoltaic generator efficiency
S_{PV}	Surface of photovoltaic panels, m^2
S_w	Wind turbine rotor swept surface, m^2
V	Wind speed, m/s
V_{MP}	Voltage at Maximum Power, V
V_{sys}	Nominal system voltage, V

Abbreviations

AC	Alternating Current
CREG	Organism in Charge Of Regulating the Energy Market
DC	Direct Current
DZD	Algerian Dinar
PV	Photovoltaic
RO	Reverse Osmosis
SDA	Algiers Electricity and Gas Distribution Company
SDC	Central and Southern Electricity and Gas Distribution Company
SDE	Eastern Electricity and Gas Distribution Company
SDO	Western Electricity and Gas Distribution Company

increase in water needs, due to population growth, the improvement of the standard of living of the populations and the development needs, make it necessary to build new installations for the production of potable water, such as seawater desalination units (energy-intensive processes)[1-3].

Therefore, in this state, the use of seawater desalination through renewable energies [4, 5], becomes an alternative and promising solution for the environment; the use of hybrid energy systems (photovoltaic-wind) [6-9], guarantees the long-term functioning [10-12].

Reverse osmosis desalination units supplied by a hybrid system have been the subject of several studies [13-19]. Mohamed and Papakadis [13], presented a tool for the design of a desalination unit using reverse osmosis technology, powered by hybrid system (PV-wind) to produce potable water, to a village of 60 inhabitants in Chania, Greece.

Koutroulis and Kolokotsa [14], propose an alternative methodology based on genetic algorithms for the optimal sizing of desalination units powered by PV and wind energy sources. Smaoui et al. [15] have developed a new algorithm for optimal sizing using the iterative optimization technique. This optimization approach determines the optimal configuration of a PV/wind/ hydrogen system. A case study was carried out to analyse a hybrid project to supply a seawater desalination unit installed on the Kerkennah islands in southern Tunisia. Spyrou and Anagnostopoulos [16] presented the optimal strategy for designing and operating an autonomous hybrid desalination system, capable of meeting the freshwater demand of an island or other remote coastal regions. The project consists of a reverse osmosis desalination unit powered by wind and solar systems, as well as a storage unit [20, 21]; a specific computer algorithm is developed to simulate in detail the entire plant operation and to carry out an economic evaluation of the investment.

The main objective of the proposed study is to ensure the desalination plant's energy demand, using the hybrid system (PV-wind turbine), for which two scenarios are needed. The first is based on the average of annual monthly values, in which the size of photovoltaic generators and wind turbines is determined from the average monthly values of each component. In the second scenario, the determination of the sizes of these two system components is based on the most unfavourable month (defined as the month that requires the greatest use of the photovoltaic and wind generator surface). Through these calculations, it will be possible to determine the size and optimization of the system, the technical-economic configuration [22-24] as well as the rate of benefit obtained from the hybrid system compared to fossil fuels.

2. Presentation of the "Honaïne" Desalination Plant

The "Honaïne" seawater desalination plant [25-27] (Fig. 1 [28]) (69 kilometres north of the town of Tlemcen, north-western Algeria), started in 2006 by the Spanish Geida group (Composed of companies: Cobra, Sadyt, Befesa and Codesa), it was operational in July 2012, with an investment amount of \$250 million. Its production capacity is 200.000 m^3/day, ensuring the supply of potable water for a population of 555,000 inhabitants [29]. The specific desalination energy of this unit is 43,800 kWh / day, with a daily power of 1825 kW.

Fig. 1. Desalination Station-Honaïne – Tlemcen [28].

3. System Overview

In order to ensure the energy requirements of the desalination unit (The station uses reverse osmosis (RO) technology) [30, 31], the system (Fig. 2) will consist of photovoltaic panels, wind turbines, batteries and inverters (to convert DC to AC).

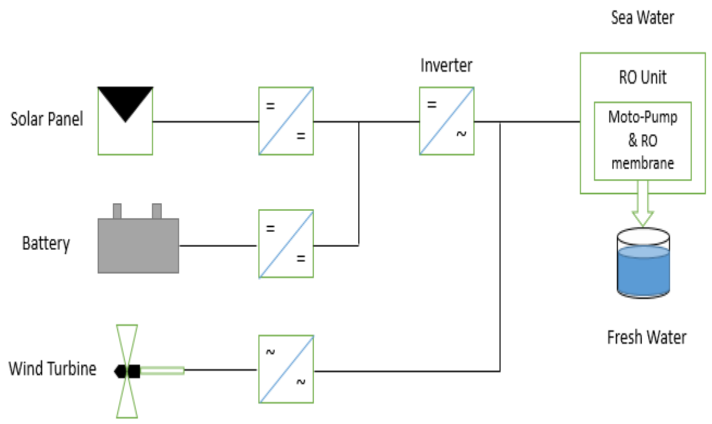


Fig. 2. Block diagram of the hybrid photovoltaic-wind-battery system.

Tables 1 to 5 represent the characteristics of each system component (PV module; wind turbine; battery; inverter [32-37]).

Table 1. Specifications of the PV module.

Name	Sunforte PM096B00
Nominal Power	333 Watt
Dimensions (L x W x H)	1559 x 1046 x 46 mm
V_{MP}	54.7 V
I_{MP}	6.09 A
Open Circuit Voltage	64.9 V
Short Circuit Current	6.58 A
Maximum System Voltage	1000 V
Module Efficiency	20.4%
Performance Guarantee	25 Years
Cost	$444,857

Table 2. Specifications of the wind turbine.

Name	Aeolos-H 50kw
Maximal Power	50Kw
Rotor Diameter	18 m
Swept Area	254.34 m^2
Efficiency	90%
Design Lifetime	20 Years
Cost	$75000

Table 3. Wind speed and power output of the wind turbine.

Wind Speed (m/s)	Power Output (kW)
3.0	0.54
3.5	0.90
4.0	1.92
4.5	3.75
5.0	5.99
5.5	8.71
6.0	11.96
6.5	16.03
7.0	20.53
7.5	25.88
8.0	32.18
8.5	38.59
9.0	45.81
9.5	50.03

Table 4. Specifications of the battery.

Name	Battery Pack ProPower
Operating voltage Pack	48 V
Storage	9600 W
Life-cycle	3500
Number of batteries in the Pack	8
Battery capacity	100 Ah
Design Lifetime	15 Years
Cost	$2034.044

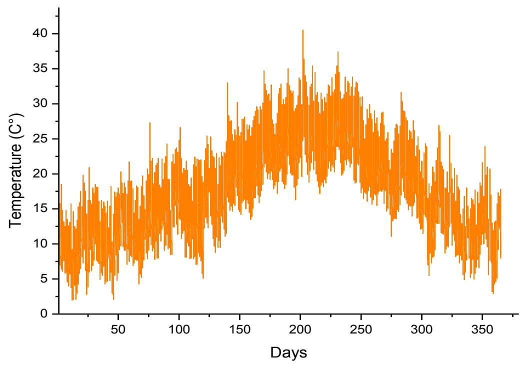
Table 5. Specifications of the inverter.

Name	CP100-Inverter
Output Type	Triple
Max power	115 kW
Output Current	160 A
Output Frequency	50Hz/60 Hz
Start voltage	500 V
Input Voltage	450-1000V
Efficiency	97.1%
Cost	$9667.425

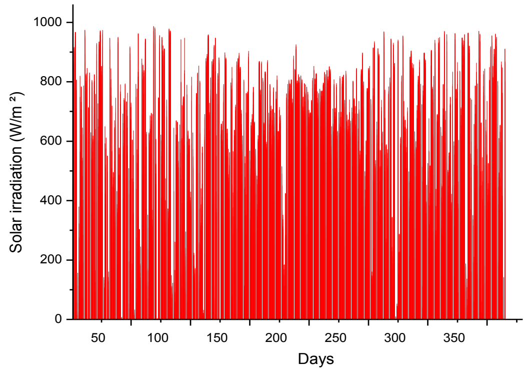
4. Sizing of Hybrid System [38, 39]

4.1. Climate data and energy received

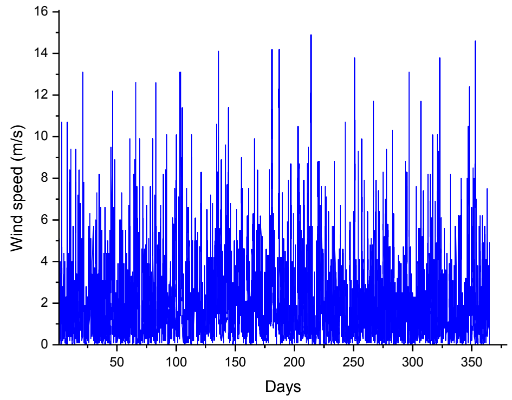
Figures 3 represent the daily climatic data [40, 41] of the studied site for one year (Honaïne-Tlemcen, Algeria). Figure 3(a) illustrates the atmospheric temperature, the latter reaches its apogee during the period from the 200th day to the 250th day with maximum temperatures at around 40°C. Figure 3(b) shows the daily solar irradiation of the studied site, this region is characterized by a large solar potential, with an annual average of 850 w/m^2. Figure 3(c) shows the daily wind speed, reaching an annual average value of 4.5 m/s.



(a)



(b)



(c)

Fig. 3. Meteorological conditions for the studied site: (a) Daily temperature (b) Daily solar irradiation- (c) Daily wind speed [40-41].

The hybrid energy received by the photovoltaic-wind system is illustrated in Fig. 4. The profile of this energy is almost constant during the period from the 20th day to the end of the year, which means that the system can cover the charge without using the batteries. On the other hand, at the beginning of the year, we notice the presence of five deficit days (2, 10, 12, 16, and the 18th day), these days represent an increased energy deficiency, hence the need to use the energy stored by the batteries.

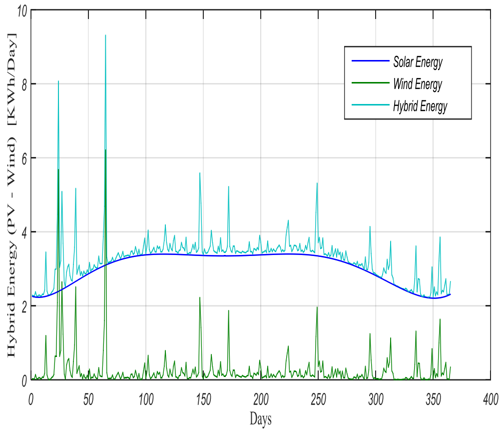


Fig. 4. Hybrid energy received (PV-wind).

4.2. System performance and determination of the worst month [38, 39]

The monthly energy produced by the system is noted $E_{PV,m}$ $(kWh\ /\ m^2)$ for photovoltaic, and $E_{w,m}$ $(kWh\ /\ m^2)$ for wind turbine (Where m = 1, 2, 3, ..., 12, represents the month of the year) and E_d the required energy. Surfaces of panels and wind turbines for 100% load coverage, during the worst month are given by:

$$S_{PV} = Max\left(\frac{E_d}{E_{PV}}\right) \tag{1}$$

$$S_{\ w} = Max\left(\frac{E_d}{E_w}\right) \tag{2}$$

4.3. Size of renewable components [38, 39]

The total energy produced by the two photovoltaic and wind generators is expressed by:

$$E_{PV}.S_{PV} + E_w.S_w = E_d \tag{3}$$

Using both renewable sources, the load is divided into two parts. If *f* is considered as the fraction of the charge given by the photovoltaic system (permeability), then the additional demand (1 - *f*) must be satisfied by the wind system. The limit values of *f* correspond to pure systems. Indeed, *f* = 1 corresponds to 100% use of photovoltaic energy and *f* = 0 represents 100% use of the wind system. The presented study is based on a hybrid system (50% photovoltaic, 50% wind), which corresponds to a permeability of *f* = 0.5.

So equations (1) and (2) become:

$$S_{PV}.E_{PV} = f.E_d \tag{4}$$

$$S_w.E_w = (1-f).E_d \tag{5}$$

with

$$E_{PV} = R_{PV}.S_{PV}.H \tag{6}$$

$$E_w = 0{,}6125.\mathrm{C_p}.S_w.V^3 \tag{7}$$

4.4. Processed scenarios [38, 39]

The two scenarios considered in this study (S = 1 and *S = 2*), are based respectively on the annual averages for each month, and the mean for the worst month of the total energy.

4.4.1. Scenario 1 (*S* = 1), annual averages for each month

In this scenario, we have determined the surfaces of the photovoltaic panels and wind turbines, based on the annual average values, which are noted $\overline{E_{PV}}$and$\overline{E_w}$.

The load is noted $\overline{E_d}$and the surfaces of the solar and wind components are given by the following equations:

$$S_{PV}^{S=1} = f\,\frac{\overline{E_d}}{\overline{E_{PV}}} \tag{8}$$

$$S_w^{S=1} = (1-f)\,\frac{\overline{E_d}}{\overline{E_w}} \tag{9}$$

4.4.2. Scenario 2 (*S* = 2), the worst month method

For this scenario, the surfaces are determined to take into account the worst month. The area required for renewable components is given by:

$$S_{PV}^{S=2} = fMax\left(\frac{\overline{E_d}}{\overline{E_{PV}}}\right) \tag{10}$$

$$S_w^{S=2} = (1-f)Max\left(\frac{\overline{E_d}}{\overline{E_w}}\right) \tag{11}$$

4.5. The autonomy coefficient R [38, 39]

The autonomy coefficient is calculated from the ratio between the total number of days of energy deficiency and the total number of operating days. In the measurement and optimization system, the autonomy criterion is $R \geq R_{min}$; R_{min} represents the minimum fraction of the allocated time for which the system must cover the request.

$$R = 1 - \frac{Nd}{Ntot} \tag{12}$$

4.6. Storage system capacity [38, 39]

The size of the storage battery is determined from the maximum requested load E_{d_max} (Maximum monthly charge). The capacity of the battery (in *Ah*)), for a period Δt is given by the following equation:

$$C_{bat} = \frac{E_{d\_max} \cdot 1000}{V_{Sys}} \cdot \frac{\Delta t}{N_m} \tag{13}$$

The actual battery capacity is determined from the capacity of a battery unit C_{bat_u}, as in the case of photovoltaic and wind generator surfaces. It is given by the following equation:

$$C_{bat\_u} = C^{te} C_{bat\_u} \tag{14}$$

where: C^{te} : Constant given by the entire part of the report $\left(\frac{C_{bat}}{C_{bat\_u}}\right)$.

5. Method of Resolution

The resolution procedure we have developed is divided into two parts. In the first part, we determined the optimal economic configuration of the renewable component, regardless of battery capacity. We have varied the fraction *f* from a step of 0.1 ($0 \leqslant f \leqslant 1$) and for each value of *f* the surface area of the renewable components is calculated from equations 8, 9, 10, and 11, using both scenarios 1 and 2. Then, taking into account the costs of the renewable components of the studied hybrid system ($f = 0.5$), we determined the optimal triplet (f, S_{PV}, S_w).

In the second part, we calculated the capacity of the batteries from equations 13 and 14 for a given period Δt. The simulation that we then used is based on a daily analysis of the S (*d*) energy contained in the batteries. $S(d)$ depends on the standby charge state (S (*d*-1)), renewable component energy ($E_{PV} + E_w$) and the consumption provided by the storage system ($\frac{E_d}{R_b}$), where R_b represents the efficiency of the batteries. If S (*d*) is less than 20% of the capacity of the batteries, this means that the demand is not entirely satisfied during this day. The day *d* is then counted as an energy deficit day. From these deficit days, we calculated the autonomy coefficient *R*.

6. Results and Discussions

6.1. Scenario 1

Figures 5 to 9 obtained from the first scenario (meteorological conditions are normal throughout the year) show the variation in the number of panels and wind turbines, their surfaces and the total cost as a function of permeability *f*. It can be seen that the permeability *f* varies from 0 to 1 with a step of 0.1, such that for $f = 0$, the system is pure wind energy, on the other hand for $f = 1$, the system is considered as pure photovoltaic. The presented study is based on a hybrid system (50% Photovoltaic, 50% Wind), which corresponds to a permeability of $f = 0.5$.

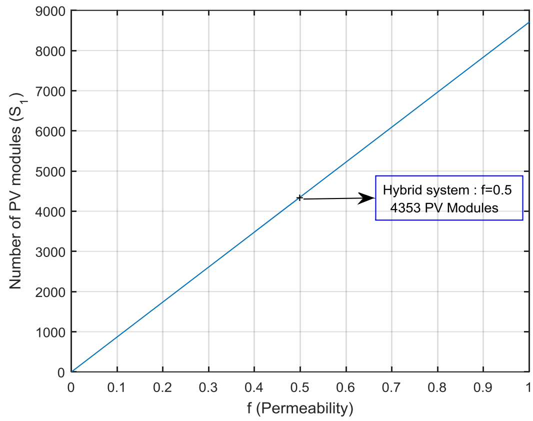


Fig. 5. Number of PV modules (scenario 1).

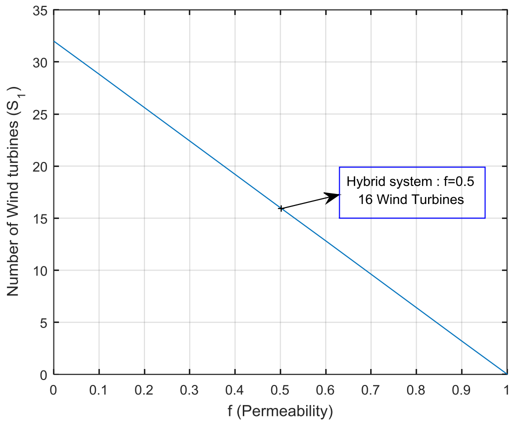


Fig. 6. Number of wind turbines (scenario 1).

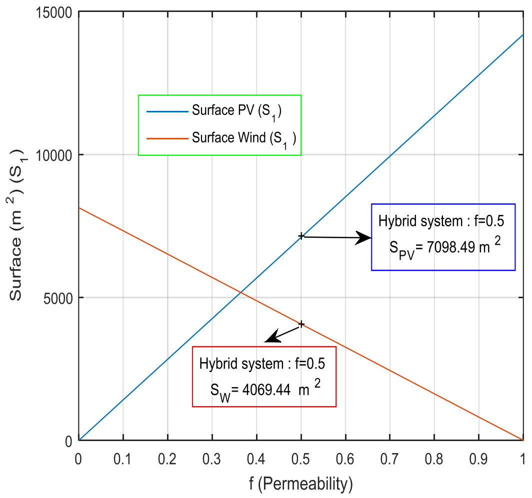


Fig. 7. Surface (scenario 1).

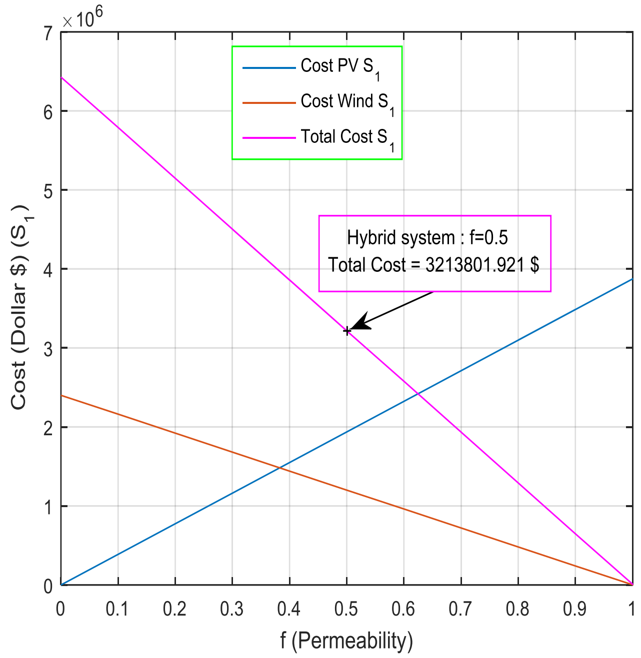


Fig. 8. Total cost (dollar ($)) (scenario 1).

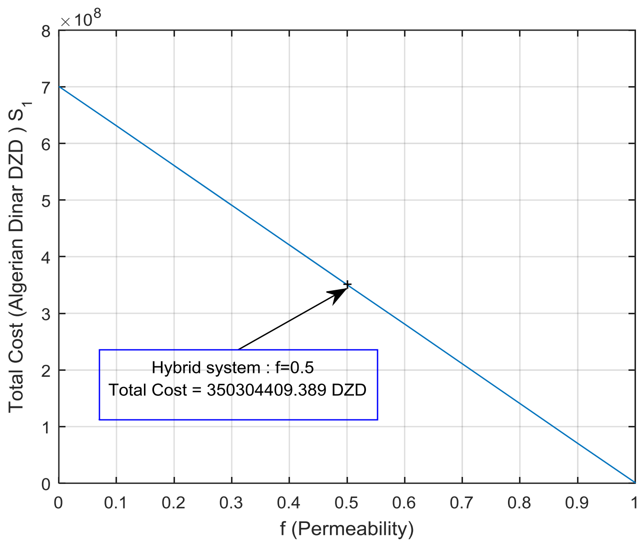


Fig. 9. Total cost (Algerian dinar DZD) (scenario 1).

According to Figs. 5 to 9 and from scenario 1, to ensure the required load, one needs:

- 4353 Panels with an area equal to S_{PV}= 7098.5 m^2;
- 16 Wind turbines with an area equal to S_W= 4069.44 m^2;

- 8 Inverters (In order to convert the direct current (DC) into alternating current (AC).

The total cost obtained from scenario 1 is:

- Total cost in dollars = $3213801.921;
- Total cost in dinars = $350304409.389 DZD **(**$1=109 DZD [42]).

6.2. Scenario 2

Figures obtained from the second scenario (weather conditions are unfavourable compared to the first one, resulting in an increase in system size) represent the variation in the number of panels and wind turbines, their surfaces and the total cost as a function of the permeability *f*.

The second scenario introduces the notion of the worst month, such as the presence of five loss-making days (2, 10, 12, 16, and the 18ème day), hence the need to use a storage system.

So to solve this energy deficit, we need:

- 951 battery. (Type of battery used : Lead-carbon battery LC1000-100Ah /C10 [34, 35])

Figures 10 to 14 show that to ensure the total energy demand for continuous operation, one needs:

- 5070 Panels with an area equal to S_{PV}= 8267.72 m^2;
- 19 Wind turbines with an area equal to S_W= 4832.46 m^2;
- 101 inverters.

The total cost obtained from Scenario 2 is:

- Total cost in dollars= $4898886.151;
- Total cost in dinars= $533978590.459 DZD**.**

It can be concluded that the complementarity between the two scenarios makes it possible to ensure the long-term continuous operation of the desalination plant.

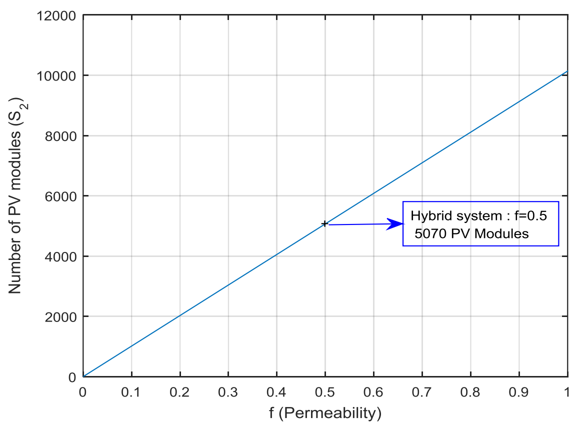


Fig. 10. Number of PV modules (scenario 2).

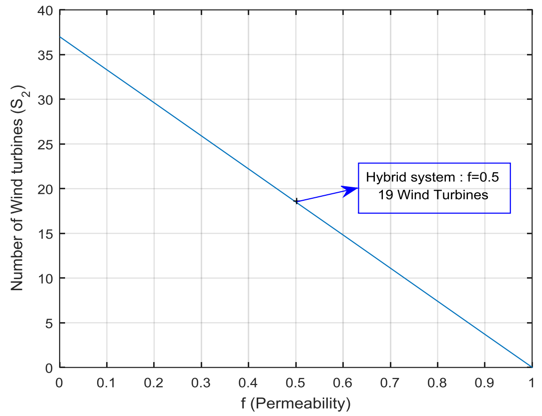


Fig. 11. Number of wind turbines (scenario 2).

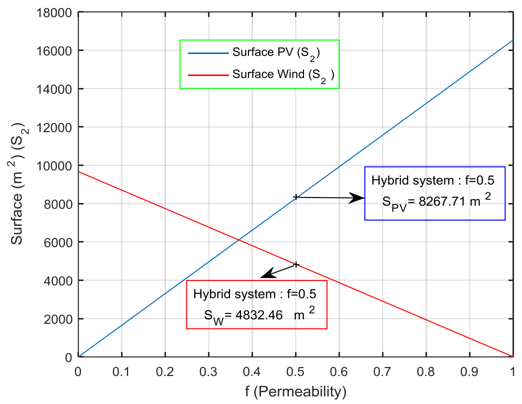


Fig. 12. Surface (scenario 2).

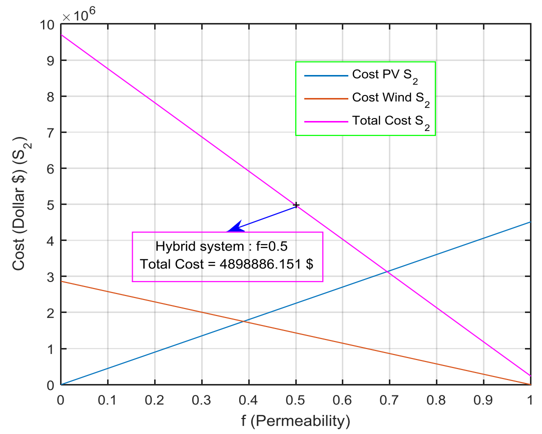


Fig. 13. Total cost (dollar ($)) (scenario 2).

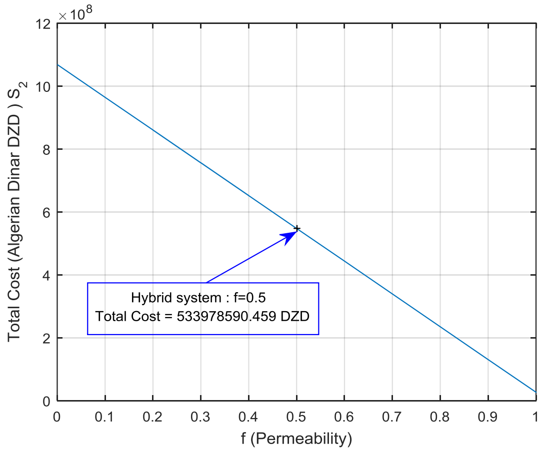


Fig. 14. Total cost (Algerian dinar DZD) (scenario 2).

6.3. Hybrid system cost compared to fossil fuels

Electricity is supplied in Algeria by four Sonelgaz subsidiaries: SDA (Algiers Electricity and Gas Distribution Company), SDC (Central and Southern Electricity and Gas Distribution Company), SDO (Western Electricity and Gas Distribution Company) and SDE (Eastern Electricity and Gas Distribution Company) [43]. A kilowatt-hour is an energy required to run a 1000-power unit for one hour. The prices per kWh of electricity in all distribution areas are the same and are set by government decree and more particularly by the CREG, the organism in charge of regulating the energy market. The latest decree is decree No. 05-182 of 18 May 2005 [44]. Pricing for professionals is charged $472 DZD/kWh [45].

The cost of supplying electricity to the desalination plant during one year of operation by fossil fuels is calculated from the following equation:

$$C_{ff} = C_{kWh} \times E \times 365 \qquad (15)$$

where

C_{ff}: Total cost using fossil fuels;

C_{kWh}: Price of 1 kWh of electricity ($);

E: Specific energy of the desalination plant (43800 kWh/Day).

- Total cost for 1 year of functioning (by fossil fuels): C_{ff} = $655,907.0091.
- Total cost for 15 years (relative to hybrid system lifetime) of functioning: C_{ff} = $9,838,605.137.

Solar PV systems require little maintenance, consisting of regular testing of cables and components, replacement of faulty modules and inverters and, in some cases, cleaning of the module [46]. Mobile parts and PV modules have a service life of 25 years. The average maintenance cost of solar panels on the market is around $4,200/MW per year [47].

The wind turbine requires very little maintenance. Indeed, at least once a year, the wind turbine must be lowered from its mast [48]. This annual maintenance optimizes the service life of the installation. The wind turbine chooses (Aeolos-H

50kw) in our study, at 5 years warranty (guaranteed against manufacturing defects, malfunctions and replacement of defective elements) [49]; the annual maintenance costs for wind turbines (25 to 150 kW) are around $4949928 [50].

- The cost of maintaining the hybrid system for a 15-year operating period is: $C_M =$ \$164474.28.
- The total cost of supplying the desalination plant using the hybrid system is: $C_{RE} =$ \$5063360.431.
- The results show that using the hybrid system allowed us to obtain a profit of 51.46% = $4775244.706 from the 7th year (7 years, 262 days, 15 hours, 58 min and 33 seconds) for a total of 15 years of functioning.

7. Conclusion

In this study, we presented an optimal sizing method, based on the results of a simulation of a hybrid system (PV-wind turbine) during a year of global solar irradiation and daily wind speed at the site of Honaïne-Tlemcen (Western Algeria), with the aim of providing sufficient electrical energy to supply a desalination station for seawater (Desalination by reverse osmosis technology, it supplies potable water for a population of about 555,000 inhabitants).

To this effect, an analysis methodology based on taking into account seasonal disturbances was established using two scenarios to ensure the continuous operation of the station. The first scenario uses the average of the monthly values per year, the second one introduces the notion of the worst month (defined as the month that requires the greatest use of the photovoltaic and wind generator surface area). The results obtained show that the complementarity of the two scenarios ensures the good functioning of the station during all the year, and this by using a number well-defined of panels, wind turbines and batteries.

On the other hand, the use of the hybrid system has enabled us to reduce the cost to 51.46% compared to fossil fuels, which gives the proposed study an important reliability, since it offers a very advantageous benefit in terms of cost and efficiency.

Based on these results, it can be seen that there is a favourable economic trend for the use of renewable energies as alternative energies, which is a promising solution for the environment in the coming decades.

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