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Development of technical economic analysis for optimal sizing of a hybrid power system: A case study of an industrial site in Tlemcen Algeria

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ABSTRACT

The current study aimed to develop an optimal sizing simulation model for an off-grid photovoltaic-wind hybrid power system of an industrial site in Algeria. The loss of power supply probability algorithm was used for sizing our hybrid system. The technical and economic evaluation for the case study showed that the storage system occupied the most critical part of the total investment cost of the hybrid system. The investment cost analysis indicated a unique optimal configuration for each size of the batteries bank. For one day's autonomy, the best size of the hybrid system corresponded to 61 PV panels and 9 wind turbines. Based on a levelized cost of energy analysis, the cost of the batteries represented for this combination is 52% of the total investment cost. The wind turbines accounted for 42% and the PV panels for only 3%. This combination of the hybrid system resulted in an energy cost that was very competitive with most European countries. However, the public energy grid cost in the case study region was still six times lower due to government subsidies. The findings are very encouraging and can help decision-makers adopt alternative and more sustainable solutions in energy policy. These results will aid in determining future research directions in Algeria's hybrid renewable energy systems.

1. Introduction

The need for quality and sustainable energy has increased due to population growth, industrialization, and technological innovation, which resulted in enhanced production capability all over the globe [1]. Furthermore, the share of intermittent renewable electricity in the energy mix has been growing, creating new challenges in power system planning and operation opportunities [2]. One of the drawbacks of fluctuant generation, for example, is non-uniform loading, which results in the underutilization of many large components, such as power transformers, especially when they approach the time of decommissioning [3]. However, smart grids' operation and planning methods can turn this disadvantage into an advantage.

Copp et al. [4] noted that more grid operators and governments aim to transition to carbon-free generation and 100% green energy to meet growing electricity demands. Arguably, this transition considers many factors, such as the cost of electricity generation and the availability of primary resources according to geographical location. For this reason, models that explore optimal trade-offs among these multiple factors are more than necessary to plan this transition. The authors proposed an optimization problem formulation to analyze the sizes of renewable generators and storage systems required to balance the total energy of the utility's electricity demand on an hourly timescale over multiple years while minimizing the desired cost. Their results showed that the amount of renewable generation required was more significant than the average demand, which motivated a regional energy trading approach.

A technical and economic optimization evaluation was performed by Farh et al. [5] to find the ideal design for an off-grid hybrid renewable energy system that contained a diesel generator, PV panels, wind turbines, and batteries as a storage system. The authors proposed an optimization method based on power system reliability enhancement and then minimizing its annualized cost for a power system dedicated to supplying a remote region in northern Saudi Arabia. Their results demonstrated the value and strength of a bonobo optimizer algorithm compared to other systems. A related paper [6] presents a bidding strategy for a virtual power plant that includes modeling uncertainties of solar generation systems by using the theory of information gap decision

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List of abbreviations

AC	Alternative Current
bat	battery
C_b	initial investment cost
C_m	operating and maintenance cost
C_r	replacement cost
DC	Direct Current
DOD	depth of discharging the battery bank
E_{bat}	Energy stored by the battery bank
E_{GA}	Total energy generated by all the hybrid system generators
E_{load}	Energy needed by the load
$G(t)$Global illuminance on a sloping planeHS	Global illuminance on a sloping plane HSHybrid System
IC_i	Initial unit cost of generator “i” (i may be PV, WT, or bat)
inv	Inverter
LCOE	Levelized Cost of Energy
LPSP	Loss of power supply probability
M_i	Operating and maintenance cost of generator “i” (i may be PV, WT, or bat)
N_i	The number of generators “i” (i may be PV, WT, or bat)
NOCT	The nominal operating temperature of the solar cell °C
P_i	Output power of the generator “i” (i may be PV, WT, or bat)
S	The area of the PV panel
SOC	State of charging the battery bank
T_c, T_o, T_a	The cell temperature, the standard temperature, the ambient temperatureη_iThe efficiency of the element “i” (i may be PV, WT, inv or bat)vThe wind speed measured each hour$v_{st}, v_n,\ v_c$ The cell temperature, the standard temperature, the ambient temperatureη_iThe efficiency of the element “i” (i may be PV, WT, inv or bat)vThe wind speed measured each hour$v_{st}, v_n,\ v_c$The start-up wind speed, minimum steady wind speed, maximum steady wind speed
γTemperature coefficientρ	Temperature coefficientρThe balance of plant cost factor

and optimal sizing to deal with solar generation fluctuations. Additionally, by analyzing the return on investment, the study was conducted to determine the short, medium, and long-term economic viability of the power system optimized by this methodology. Although it was possible to compensate for fluctuations in solar generation, the capital costs were high. The investigators concluded that, in the short term, it was more viable to use a supply strategy based on modeling uncertainties than to increase the storage capacity.

Fossil fuels for electricity production and running automobiles are the major sectors generating air pollution [7]. Reducing automobile emissions by applying clean electric power could alleviate pollution. Meaningful progress has recently been made in many areas of electricity production from renewable energies [7]. But these advances are uneven from region to region. In Africa, almost all electricity is generated from fossil fuels. If the current dependence on such fuels continues, the continent’s economic growth will be environmentally unsustainable, as reported by Ref. [8]. To counteract this trend, countries such as Algeria have embarked on ambitious programs for the development of renewable energies as well as enhancing energy efficiency [9,10].

Several technical and economic optimization algorithms have been developed over the last decade to avoid the problem of the oversizing of hybrid systems. Luna-Rubio et al. [11] classified sizing methods of hybrid systems into four categories, namely: probabilistic, analytical, iterative, and hybrid. According to the authors, the first category was not accurate, whereas, with the second, the system’s performance could be precisely assessed. The last two types allowed for optimal multi-objective sizing by minimizing the investment cost and the greenhouse gases. Furthermore, another review on optimization techniques was conducted by Ref. [12] to achieve optimal sizing of PV-wind hybrid power systems. The authors classified optimization sizing methods into four categories: software tools, conventional, non-conventional, and hybrid. Software tools are commercially available and allow users to choose their hybrid system. However, software’s present drawbacks include black box coding, high computation time, limitation of optimal function, and complex management of constraints [13]. Moreover, the technical and economic feasibility study of hybrid systems for a small remote area has been conducted using software tools [14,15].

Conventional methodologies allow designers to find the best configuration of a hybrid energy system by analyzing single or multiple performance indexes. The calculation process changes one or more performance indicators each iteration to improve the quality of possible solutions until reaching an optimal configuration [12]. Kaldellis et al. [16] proposed an approach for optimal designs for stand-alone wind-PV hybrid systems by having a continuous power supply and a specific economic performance criterion. Likewise, Guinot et al. [17] employed an iterative process to minimize two performance indicators, namely the levelized cost of energy and the duration of power supply failure. Barade and Roy [18] developed a simple methodology where the photovoltaic–diesel-battery hybrid system sizing was analyzed based on less energy cost. At the same time, a probabilistic approach was used to satisfy the energy balances under resource uncertainty. Hosseinalizadeh et al. [19] investigated techno-economic system optimization by simulating the behavior of different combinations of renewable energy units with various sizing, including wind turbines, photovoltaic panels, fuel cells, and battery banks. Optimizing all components was obtained by introducing balancing constraints and an economic objective function. Finally, to examine the feasibility and performance of a PV/Diesel/Battery hybrid system dedicated to electrifying rural communities. Alberizzi et al. [20] employed a mixed-integer linear programming algorithm to find an optimal solution by minimizing the energy cost while ensuring that the energy produced meets a continuous load demand.

Bio-inspired meta-heuristic algorithms have demonstrated a remarkable ability to solve various complex problems by finding the optimal solution from a finite number of existing solutions. These algorithms are motivated by the natural evolution of species’ social behavior. Various researchers have applied such optimization techniques for hybrid systems. For example, open space particle swarm optimization (PSO) was proposed by Ref. [21] for optimal sizing. A fitness function simulation was performed to achieve the lowest life cycle cost by a zero-loss power supply probability constraint. It was also employed by Refs. [22–24] to seek the optimal system configuration, which maximizes the reliability of electrical power supplies and minimizes the total system cost. Yahiaoui et al. [25] applied PSO to optimize the hybrid PV-Diesel-Storage systems for a remote rural city in Algeria. Their developed algorithm simultaneously minimized the system’s total cost, power supply probability, and gas emissions loss. Likewise, the genetic algorithm is also suitable for optimizing hybrid systems. Genetic algorithms were applied in Refs. [26–28] for optimum sizing of a hybrid PV/wind system. Bio-inspired optimization algorithms were used to solve the sizing problem of hybrid solar and wind systems like the work reported by Ref. [29] based on ontology domains. A multi-objective evolutionary algorithm was proposed by Ref. [15] for designing a hybrid power system where the optimization technique was based on decomposition with a localized penalty-based boundary intersection. Finally, Diab et al. [30] conducted a detailed comparison of various evolutionary algorithms. They proved the superiority of some methods in terms of convergence speed, but the authors noted that all eventually converged to the same values.

A significant drawback in complex optimization problems is premature convergence. Sometimes a technique fails to find the optimal solution, or it takes a long time to come out of local maxima or minima. Hybrid methods have been applied successfully to exploit the advantages of two or more optimization techniques to solve such premature convergence problems. Such procedures appear more potent than individual methods [11,12]. A hybrid Particle Swarm Optimization-Gravitational Search Algorithm was utilized by Ref. [31] to simultaneously minimize power losses and improve the voltage profile in a radial distribution system.

Hybrid systems offer an alternative solution to reduce the need for fossil fuels by choosing the right combination of renewable energy sources. Such schemes usually consist of renewable resources like solar photovoltaic and wind power that have significant potential and are regionally competitive [24]. Since these resources are intermittent, other conventional energy sources such as microturbines or storage systems are often added [32,33]. Lithium-ion batteries have recently replaced almost all other batteries because of low losses and excellent energy density at reduced weight [14]. New lithium-ion battery technologies have emerged, such as LiFePo4, whose performances are even better, with a depth of discharge and a lifetime more critical. Modeling the battery's charge state is essential to better size the necessary storage capacity. The battery state of charge requires the exact knowledge of the previous state of charge, the current energy produced by the different types of generators, the present energy needed by the load, and the efficiency of the other elements involved in the charge or discharge operation. Deep discharges should be avoided because they can reduce the battery life to half. Resistance to deep discharge depends on the battery type. Particularly efficient, the LiFePo4 battery is becoming increasingly popular in new hybrid installations. It is resistant and allows a more significant number of charge/discharge cycles for a life exceeding 10 years [14].

Conventional methodologies based on average values or worst scenarios may lead to oversizing system components. It can be argued that iterative, bio-inspired, and hybrid techniques are suitable for optimization with a multi-objective function. However, such approaches are more complicated and require considerable computer processing. An efficient iterative method can get around this problem by allowing for analysis of the behavior of a hybrid system and finding the optimal configuration [11,16].

The current study aimed to develop an optimal sizing simulation model for an off-grid photovoltaic-wind hybrid power system for technical and economic analysis of an industrial site in Algeria in northwest Africa. Each component of the hybrid system was first modeled, then the scheme was evaluated to allow for the best choice of components to identify the optimal configuration. The renewable energy generators were modeled to assess the effect of component amount on system behavior and the cost of its output energy. The most economical configuration was then recommended while respecting the technical constraint of zero loss of power supply probability.

2. Materials and methods

2.1. Case study site

Located in the west of Algeria at the latitude of 34.97° and longitude of 1.44°, a private company has been operating since 1994 and is a pioneer in producing carob powders. This company intends to acquire an off-grid renewable hybrid energy power system for supplying the administrative building. The power needed by the latter is a low-power generation system consisting of photovoltaic panels and wind turbines. As the reliability of the off-grid power supply is required, and these renewable resources are intermittent, a battery storage system must be integrated into the hybrid system.

The measurement of the meteorological factors of the site is fundamental for evaluating exploitable energy potentials. That is why one has installed sensors and measuring devices for collecting irradiation, temperature, wind speed, and power consumption values. Thereby, the use of meteorological data collected every hour from the site with different climatic characteristics allows a more precise analysis of the influence of the climate on the hybrid system operation.

All these meteorological measurements provide valuable data for calculating the available hourly photovoltaic and wind powers. On the other hand, the power demand of the load, mainly due to the office devices during the day and the lighting and irrigation during the night, is deducted from the energy meter of the administrative building.

2.2. Modeling of renewable generators

The optimal sizing of the PV-Wind hybrid system required a reliable mathematical model for each component or generator. Thus, the characteristics of each element must be easily deduced and well-evaluated from this model. This way, the module with the most convenient features will dominate in the final configuration.

2.2.1. Solar PV generator

The output power of a photovoltaic generator for each hour "t" can be calculated using equation (1) [16]:

$$P_{PV}(t) = N_{PV}\eta_{PV}G(t) \tag{1}$$

N_{PV}: The number of PV panels

η_{PV}: The instantaneous efficiency of the photovoltaic panel is calculated as (Equation (2)):

$$\eta_{PV} = \eta_r(1-\gamma(T_c-T_o)) \tag{2}$$

S: The area of the PV panel

$G(t)$: The global illuminance on a sloping plane

η_r: The reference yield of the photovoltaic panel under standard conditions

γ: Temperature coefficient determined experimentally by the manufacturer, taken from PV module catalog (−0.41%/°C).

T_c, T_o: The cell temperature (°C) and the standard temperature respectively which varies depending on the illumination and the ambient temperature as follows [16]:

$$T_c = T_a(t) + \frac{NOCT-20}{800}G(t) \tag{3}$$

2.3. NOCT: the nominal operating temperature of the solar cell °C

T_a : The ambient temperature (°C).

2.3.1. Wind generator

The following Equation (4) was used for modeling the wind turbine [24,28,29,34]:

$$P_{WT}(t) = \begin{cases} 0 \quad for\ v(t) < v_{st} \\ P_N\dfrac{v(t)-v_{st}}{v_n-v_{st}} \quad for\ v_{st} \le v(t) \le v_n \\ P_N \quad for\ v_n \le v(t) \le v_c \\ 0 \quad for\ v(t) \ge v_c \end{cases} \tag{4}$$

where:

P_{WT}: The output power of the wind turbine.

v: The wind speed measured each hour (m/s); v_{st}: The start-up wind speed (m/s); v_n: The minimum steady wind speed corresponding to the rated output power (m/s); v_c: The maximum steady wind speed corresponding to the rated output power (m/s);

P_N: The rated output power of the wind turbine.

2.3.2. Storage system

During charging operation, when the total output power of all generators is greater than the load power, the stored energy "$E_{bat}(t)$" in the battery at the hour "t" increases as follows (Equation (5)) where the self-discharge factor is taken as zero [33,34]:

$$E_{bat}(t) = E_{bat}(t-1) + \left[E_{GA}(t) - \frac{E_{load}(t)}{\eta_{inv}} \right] \eta_{bat} \tag{5}$$

During discharging operation, when the total output power of all generators is less than the load power, the stored energy "$E_{bat}(t)$" in the battery at the hour "t" decreases as follows (Equation (6)):

$$E_{bat}(t) = E_{bat}(t-1) - \left(\frac{E_{load}(t)}{\eta_{inv}} - E_{GA}(t) \right) \eta_{bat} \tag{6}$$

$E_{GA}(t)$: The total energy generated by all the hybrid system generators at the hour "t" $E_{load}(t)$: The load demand at the hour "t",

η_{inv}, η_{bat}: Efficiencies of the inverter and the battery charging/discharging controller

The battery bank state of charge "$SOC(t)$" is the percentage of stored energy compared to its maximum storage capacity and is represented by Equation (7) [34].

$$SOC(t) = \frac{E_{bat}(t)}{C_{bat} \times V_{bat}} \tag{7}$$

"V_{bat}": The voltage of batteries

C_{bat}: The total amount of electricity that a battery bank can provide after being fully charged

The battery bank depth of discharge "$DOD(t)$" is the percentage of energy discharged from the battery. It is given as a percentage of its capacity (Equation (8)).

$$DOD(t) = \frac{C_{bat} \times V_{bat} - E_{bat}(t)}{C_{bat} \times V_{bat}} \tag{8}$$

2.3.3. The inverter and the charge/discharge controller

Once the correct configuration of the system has been established, the charge/discharge controller must satisfy two main technical characteristics according to the storage system: the maximum power and the maximum charge/discharge current. An inverter delivering a pseudo-sinusoidal waveform may be sufficient for administration equipment such as light bulbs and personal computers. It is the intermediate piece between the DC bus and the load. It must be compatible with the storage system. Its input voltage must withstand the voltage of the storage system, and its output voltage must match the AC voltage of the load, whereas its power should be slightly larger than the peak power of the load [35].

2.4. Problem statement

One expects PV/Wind hybrid systems to play a vital role in providing electricity supply in the case study region. The quality of all the components of the hybrid system depends on the lifetime, technical performance, and warranty the manufacturer provides. Prior knowledge of the technical performances specified by manufacturers for all generators is essential to lead to reasonable estimations of its power undertaken under meteorological conditions of the site [17]. In addition, concerning quality/price ratios, the components must be chosen to be adaptable to each other in terms of rated power and rated voltage. Table 1 summarizes the technical specifications of all selected elements.

The main task in this study was to find the optimal configuration of the chosen hybrid system to meet the power demands of the study site. In terms of technical analysis, multiple approaches were applied to pull off the optimal configurations of the hybrid system. The LPSP (Loss of power supply probability) method was chosen. Subsequently, and from configurations obtained for a zero LPSP, the investigation proceeded to economic analysis, from which the most economical design with the lowest energy cost was chosen. The structure or architecture of the proposed hybrid system comprises renewable energy generators, power conversion units (the inverter and the charging/discharging controller), lithium-ion batteries, and the load (Fig. 1).

Table 1
Technical specifications of selected components for the hybrid system.

PV panel					
Rated power	Rated voltage	Size	Efficiency	Price (€)	Lifetime
300 W	36.19 V	1.752m^2	17.1%	160	25 years
Six bladed Wind turbine					
Rated power	Rated voltage	Starting wind speed	Rated wind speed	Price (€)	Lifetime
800 W	48VDC	1.8 m/s	11.5 m/s	322.90	15 years
Battery					
Capacity	Rated voltage	DOD	Efficiency	Price (€)	Lifetime
2.5 kW h	48 V	75%	95%	1171.51	6 years

2.4.1. Output power of the selected renewable generators and load profiles

The measurement of meteorological parameters is essential for evaluating the exploitable renewable resources of the study site. Installed sensors and measuring devices collected hourly values of the power requested by the load (administrative building), irradiation, temperature, and wind speed, which allowed for a more precise analysis of the influence of climate on the operation of the hybrid system. Meteorological and load data was taken on the study site for 16 days in February 2020. Irradiation and temperature values were carried manually every hour of the day at four points on the rooftop of the administrative block, where the pyrometer is placed on support inclined at 30° and oriented towards the south. The mean value of the four values provides the hourly irradiation and temperature. Measurements were taken in winter conditions where the ambient temperature does not exceed 23 °C. So we assumed that the efficiency of the PV panels was not affected to a level that would need to be considered. Using equations (1)–(3), we calculated the hourly power distribution the selected PV panel can extract under the irradiation and temperature conditions recorded at the study site (Fig. 2).

Although the measurements were taken in February when days were short and the number of sunshine hours was relatively low, the measured values indicated a substantial available solar potential. In addition, the outside temperature was ideal for the efficient operation of the photovoltaic panels. Thus, exploiting the solar potential in this place is the best way to ensure a clean electricity supply for the load.

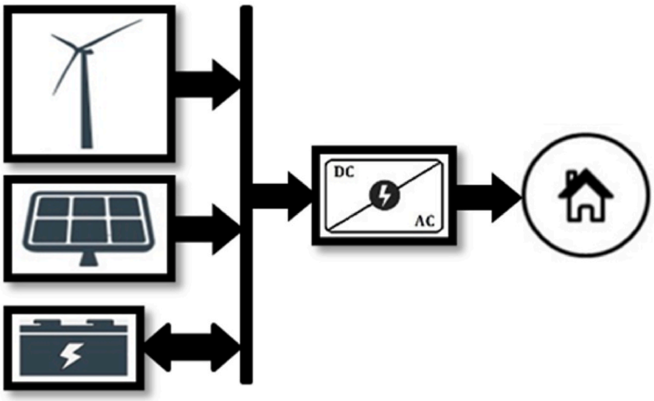

Fig. 1. The architecture of the proposed hybrid system comprises renewable energy generators, power conversion units (the inverter and the charging/discharging controller), lithium-ion batteries, and the load.

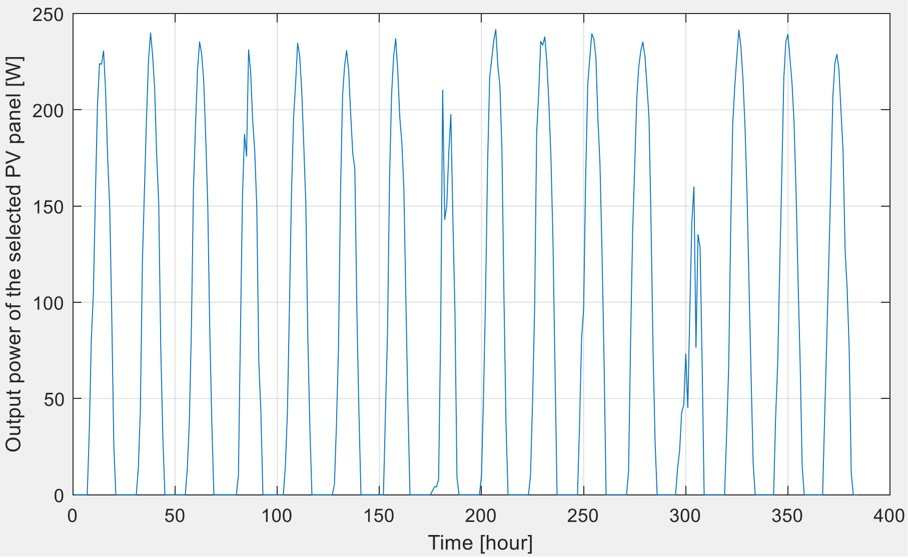

Fig. 2. The hourly output power of the selected PV panel during the 16-day measurement period.

The wind speed at the height of 10 m is also measured simultaneously as the irradiation and the temperature. Using equation (4), one calculated the hourly power distribution the selected wind turbine can extract under the meteorological factors recorded at the study site (Fig. 3). The output power fluctuates, with more winds blowing in the afternoon during the measurement period. Unfortunately, this short measurement period did not match the seasonal wind known on the study site. The six-bladed horizontal axis wind turbine was selected because its low start-up speed matches the low wind speeds at the study site.

The daily load profile shown in Fig. 4 reflects the energy consumption of administrative activities during the day and irrigation and lighting at night. The load is vital during the working hours from 8:00 a.m. until the peak consumption at 11:00 a.m. From the zoom close-up made for one day at 300 h (see RHS of Fig. 4), the peak of the curve (i.e., 9200 W) occurs at 11 a.m., whereas at nighttime, the power load requirement drops to 4700 W. The latter indicates a constant electrical consumption (i.e., load), due mainly to nighttime lighting and irrigation.

2.4.2. *Technical sizing algorithms*

The objective was to find the optimal configuration of the wind-photovoltaic hybrid stand-alone power system based on the analysis of the effect of each component size, using technical performance criteria. In this case, the LPSP method of sizing hybrid systems was applied where the loss probability was taken as nil during the measurement period. To better see the effect of increasing the amount of one component on another component, the amount of the third component was kept constant. For each increment, amounts of components must satisfy the electrical load having the profile illustrated in Fig. 4 with zero LPSP. For example, when the number of wind turbines is increasing for the proper functioning of the global system, the storage capacity size is set constant to analyze the necessary PV panels. Then, the number of wind turbines was incremented gradually, and a simulation for each increment was made for the functioning of the hybrid system and checked to see if the probability of loss of the power supply was zero. If this was not achieved, the number of PV panels increased until a zero LPSP was obtained. These calculations were repeated till the maximum amount of wind turbines was reached. The flowchart in Fig. 5 shows the curve of the number of PV panels versus the number of wind turbines for a given storage capacity.

Plot N_{PV} VS N_{WT} corresponding to the given storage capacity "E_{bat}".

$N_{WT} = N_{WT} + 1$

No.

Yes.

Is $N_{WT} > N_{WTmax}$?

Initializing the amount of PV panels "N_{PV}"

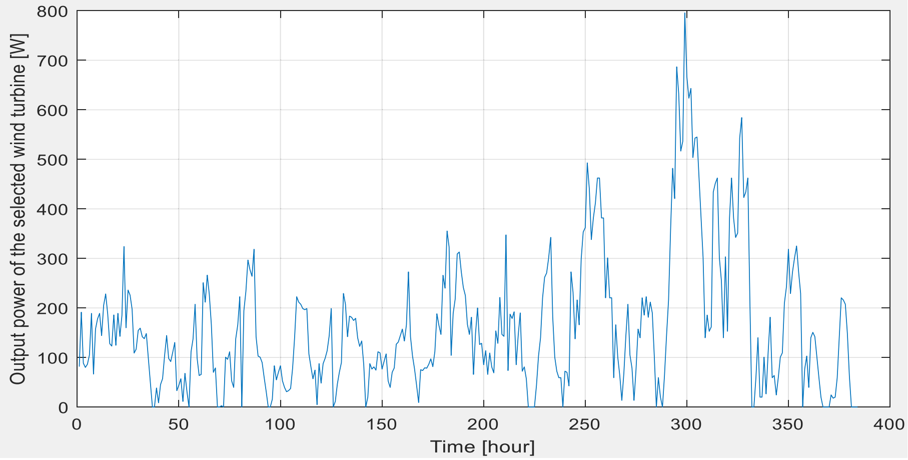

Fig. 3. The hourly output power of the selected wind turbine during the 16-day measurement period.

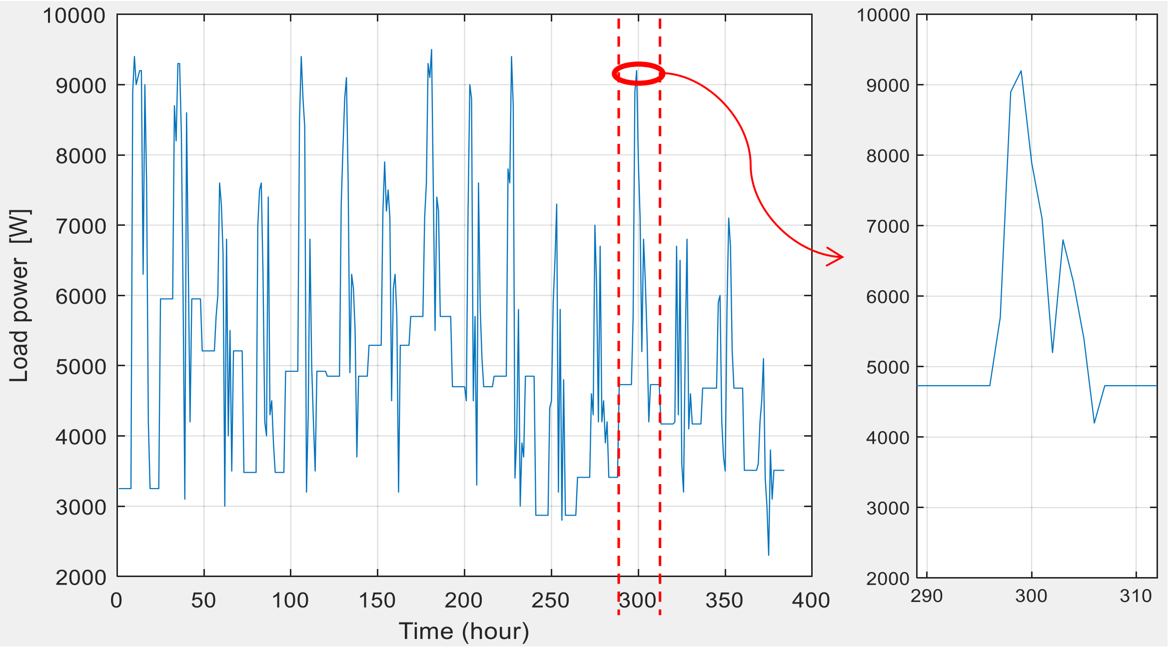

Fig. 4. The hourly power demand for the 16-day measurement period.

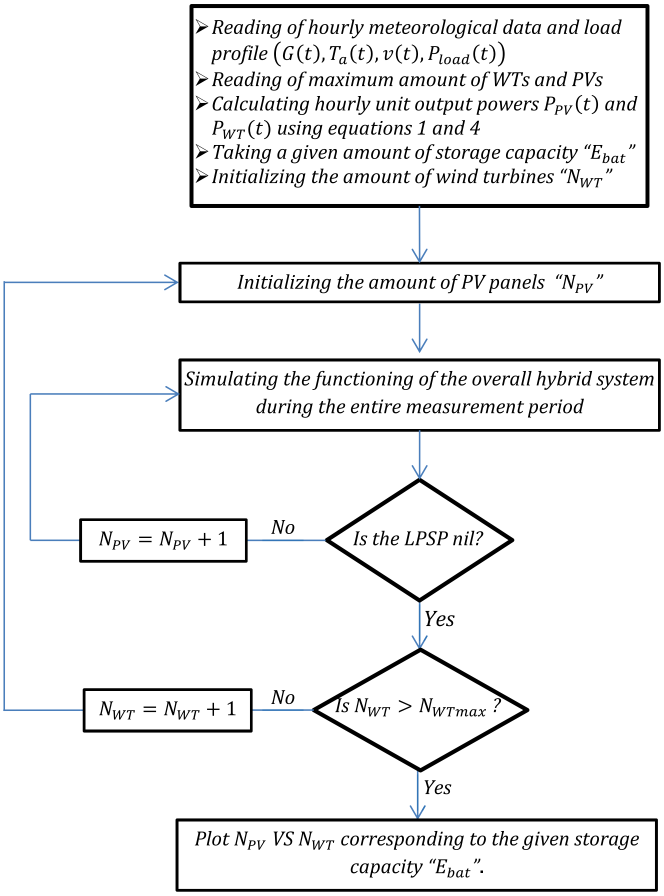

Fig. 5. Flowchart for determining number of PV panels as a function of number of wind turbi

omponent.
$N_{PV} = N_{PV} + 1$
No.

Yes.
Is the LPSP nil?
Simulating the functioning of the overall hybrid system during the entire measurement period.

- *Reading of hourly meteorological data and load profile* $(G(t), T_a(t), v(t), P_{load}(t))$
- *Reading of maximum amount of WTs and PVs*
- *Calculating hourly unit output powers* $P_{PV}(t)$ *and* $P_{WT}(t)$ *using equations 1 and 4*
- *Taking a given amount of storage capacity "*E_{bat}*"*
- *Initializing the amount of wind turbines "*N_{WT}*"*

2.4.3. Economic sizing of the hybrid system

The main goal of the economic analysis was to find the best hybrid system configuration, which leads to a minimized investment cost while meeting technical constraints such as reliability. The evaluation of the economic performance function must be given for a chosen reference period. Therefore, this function included the initial investment cost ″C_b″ (costs of purchasing and installing all components), the cost of operating and maintenance ″C_m″, and the replacement cost ″C_r″ of some features which have a lifetime lower than the reference period [17,26].

$$f = C_b + C_m + C_r \tag{9}$$

The initial investment cost ″C_b″ included the purchase and installation costs of each component of the hybrid system (i.e., PV panels, wind turbines, batteries with charge controllers, and the inverter). The initial cost of PV and WT generators was increased by a factor ″ρ″, which corresponded to the balance of plant cost. This factor was added to provide the infrastructure and support needed to keep the hybrid system running stably and safely (Equation (10)).

$$C_b = (1 + \rho)(N_{PV}\ IC_{PV} + N_{WT}\ IC_{WT}) + IC_{inv} + C_{bat}\ IC_{Bat} \tag{10}$$

The operating and maintenance cost, "C_m" of the hybrid system, was the sum of expenses required to operate and maintain each system component (Equation (11)).

$$C_m = N_{PV}\ M_{PV} + N_{WT}\ M_{WT} + M_{inv} + C_{bat}\ M_{bat} \tag{11}$$

The replacement cost, ″C_r″ was the cost of replacing each component with a lifetime lower than the reference period, which was equal to those of photovoltaic panels. The replacement cost could differ from the initial purchase cost (Equation (12)).

$$C_r = N_{WT}\ CR_{WT} + CR_{inv} + Q_{bat}\ CR_{Bat} \tag{12}$$

In this study, the salvage value in replaced components was considered. It is the equivalent quantity of remaining life for a part of the electrical system at the end of the hybrid system's lifetime. A linear evaluation was employed in which the salvage value of a component was directly proportional to its remaining life [36]. When the replacement cost is different from the initial cost, the salvage value is calculated in terms of replacement cost rather than initial capital cost (Equation (13)).

$$pr_i = CR_i \frac{T - nr_i T_i}{T_i} \tag{13}$$

pr_i is the salvage cost of a replaced component
T is the hybrid system lifetime
T_i is the component lifetime
nr_i is how often a component is replaced
″i″ could be WT, inv, or bat

The same algorithm is followed to analyze the economic function in technical analysis. But for each establishment of the proper sizes (LPSP = 0), the corresponding economic function was calculated as given by Equation (9). For example, to analyze the economic function when the wind turbine's amount was increasing while ensuring a zero probability of loss of the power supply, the algorithm of Fig. 5 was followed. After finishing the internal loop, a configuration with an LPSP nil was established, and the corresponding economic function was calculated and followed by the remaining steps.

In addition to its importance in deciding whether to go ahead with a project, the levelized cost of energy (LCOE) is also a metric factor allowing financial analysts to assess different power generation technologies. It compares electric power generation technologies despite differences in lifetimes, investment costs, project size, and even the advantages and disadvantages of each project. The LCOE was calculated by taking the total investment cost associated with the project divided by the total electricity production over its lifetime (Equation 14). So, the LCOE reflected the per-unit cost of the energy produced by the project regardless of its primary resources [28].

$$\mathrm{LCOE} = \frac{\sum_{1}^{n} \mathrm{IC_t}/(1+\mathrm{r})^{\mathrm{t}}}{\sum_{1}^{n} \mathrm{E_t}/(1+\mathrm{r})^{\mathrm{t}}} \tag{14}$$

$\mathrm{IC_t}$: The investment cost during year ″t″
$\mathrm{E_t}$: The energy generated during year ″t″
r: The discount rate of the project
n: The life of the project

The company required a power supply lasting at least one day of autonomy. According to measurements taken at the study site, the average daily energy needed by the load equaled 120 kW h, which corresponded to energy stored by 48 batteries, where the capacity of each battery was 2.5 kWh (see Table 1). The objective of this economic analysis step was to find the best hybrid system configuration which would lead to a minimum investment cost. In this context, the investment cost given by Equation (9) was programmed and simulated to produce curves of total investment cost as a function of the number of PV panels at various constant WTs and the number of wind turbines at constant PV panels.

3. Results and discussions

3.1. Technic analysis of the hybrid system

The simulation based on the process shown in Fig. 5 resulted in the curves giving the wind turbines amount versus the number of PV panels for a given size of the bank of batteries (Fig. 6). For each storage capacity, the number of wind turbines decreased with the increasing number of PV panels. For example, for a bank of 40 batteries, the number of wind turbines decreased almost linearly from 48 to 13 when the number of PV panels increased from 0 to 55. Increasing the number of PV panels beyond 55 had no significant effect. The number of wind turbines remained almost invariant beyond 55 PV panels. This invariance means that at this level of storage capacity, the system cannot function with a zero LPSP without the presence of a sufficient number of wind turbines. In the case of a lower storage capacity, it would be appropriate to use a hybrid system with a majority of wind turbines because of solar energy's solid intermittent nature, which needs a substantial storage capacity. Curves corresponding to 50, 60, and 80 batteries were more linear and closer to each other. This proximity meant that increasing the storage system did not oversize the hybrid system but increased its autonomy.

Likewise, to better analyze the effect of storage capacity, a simulation of the variation in the number of batteries needed by a hybrid system as a function of the number of PV panels for a given or constant number of wind turbines is shown in Fig. 7. All curves showed that increasing the number of PV panels decreases the required storage capacity. The slope of the curves leveled off after a certain number of PV panels (i.e., the number of batteries became independent of the number of PV panels). For example, for a system with only PV panels (i.e., 00 WTs), the number of PV panels must be no less than 66, corresponding to 100 batteries. This result is evident because the battery bank must be large to store the large surplus of PV energy during the day to restore it at night. Adding many wind turbines makes the storage capacity needed less critical. For example, for a hybrid system with 70 wind turbines (70 WTs), the necessary storage capacity is meager (20 batteries at 3 PV panels). By increasing the number of PV panels beyond 10, the storage capacity becomes almost constant at around 12 batteries, as shown by the shallow slope of the line (Fig. 7).

Simulation of the variation in the number of batteries needed by the hybrid system as a function of the number of wind turbines for a constant number of PV panels is shown in Fig. 8. Increasing the number of wind turbines decreased the required battery storage capacity for all curves from 00 to 80 PVs. For example, for a hybrid system with only wind turbines (i.e., 00 PVs), the number of wind turbines must be no less than 41, corresponding to 100 batteries. Increasing the number of wind turbines led to a rapid decrease in required storage capacity and reached 23 batteries for 70 WTs at 00 PVs). For a hybrid system with 80 PV panels (80 PVs), the necessary storage capacity was 60 batteries at 2 wind turbines (Fig. 8). By increasing the number of wind turbines to 70, the required energy storage capacity decreased to 12 batteries.

It should be noted that the number of wind turbines (WTs) significantly affects the storage capacity curves (see Figs. 7 and 8). In contrast, the number of PV panels makes very little difference (Fig. 7). So, it can be suggested that a reduction in the capacities of the battery bank is recommended, along with a predominance of wind turbines. Configurations obtained by the technical analysis meet the technical requirement that the probability of loss of power supply is zero. This makes these configurations may be not optimal and oversized.

3.2. Economic analysis of the hybrid system

Private companies, including private investment-funded entities, play a significant role in promoting and exploiting renewable energies. It can be argued that oversizing and incorrect choices for hybrid system configuration inflates the investment cost and thus reduces the attractiveness of a project. The use of investment cost analysis to evaluate a project is therefore crucial. The current study simulated the total investment cost as a function of the number of PV panels while setting the number of wind turbines at constant values. The number of batteries was calculated for each point so that the loss of power supply probability was nil. The simulation results of total investment cost as a function of the

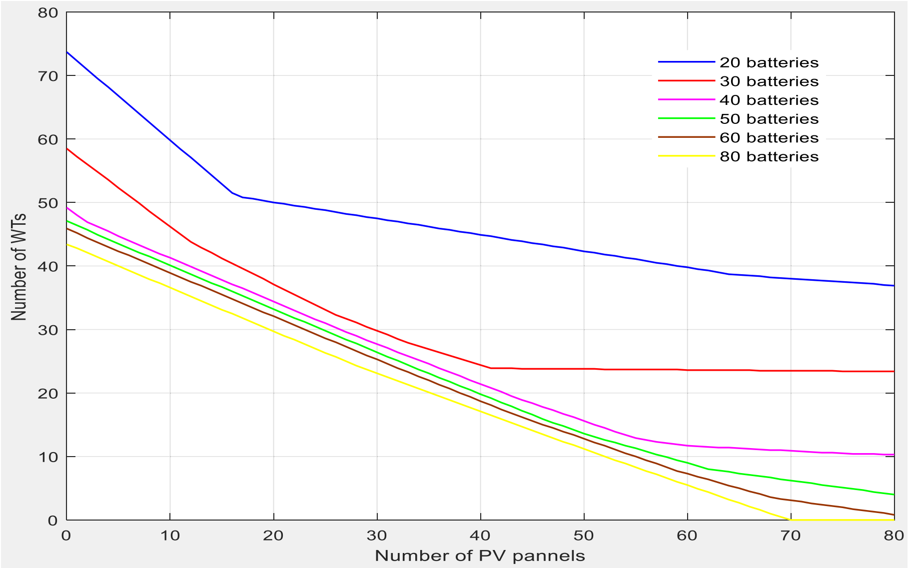

Fig. 6. Number of wind turbines as a function of number of PV panels at various constant battery loadings ranging from 20 to 80.

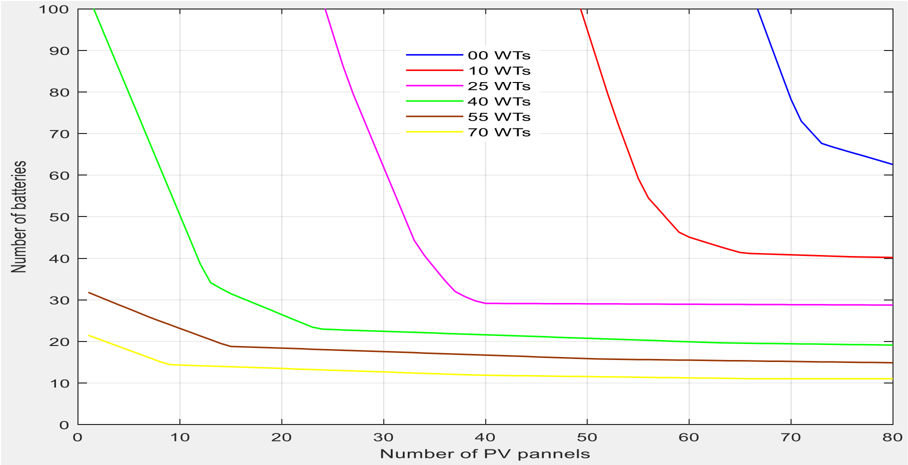

Fig. 7. Number of batteries as a function of number of PV panels at various constant wind turbine loadings ranging from 0 to 70 WTs.

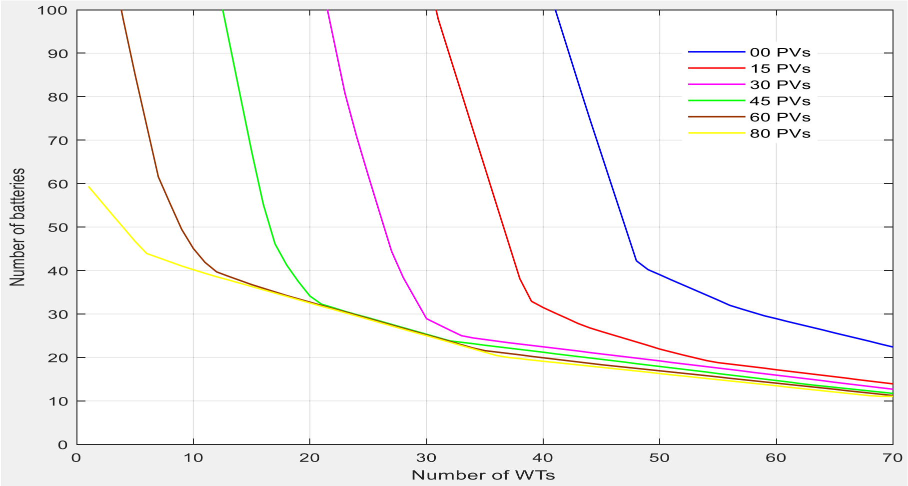

Fig. 8. Number of batteries as a function of number of wind turbines at various constant PV loadings ranging from 0 to 80 PVs.

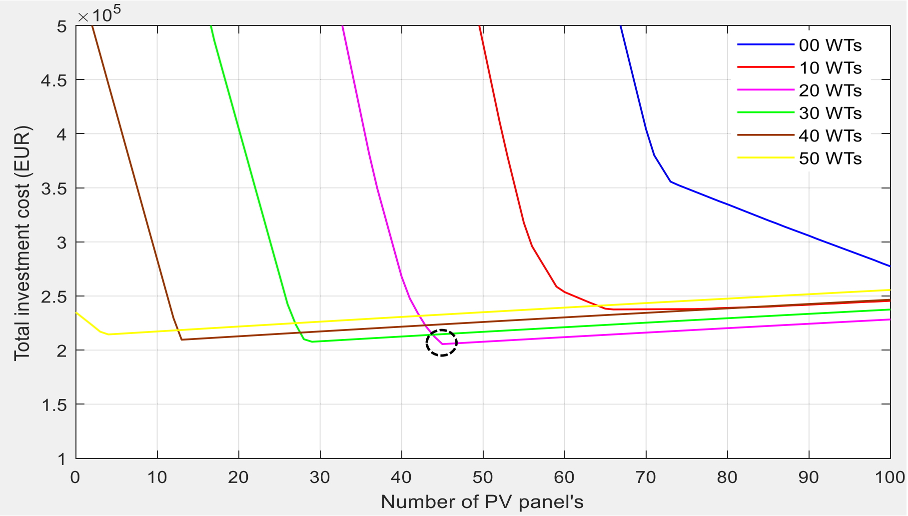

Fig. 9. Total Investment cost as a function of number of PV panels at various constant number of wind turbines ranging from 0 to 50 WTs.

number of PV panels at various constant numbers of wind turbines ranging from 0 to 50 WTs are shown in Fig. 9. Each curve had a minimum value. For example, at 20 WTs, the minimum in the curve was 45 PV panels (see the dashed circle in Fig. 9). This setup corresponded to a minimum total investment cost of 200 k€.

The results of the analysis of the effect of the number of wind turbines on the investment cost are shown in Fig. 10. For each curve, the PV array size (i.e., number of panels) was kept constant, ranging from 0 to 75 PVs, while the number of batteries was calculated for each point so that the loss of power supply probability was nil. Each of the curves had a minimum total investment cost value. For example, the curve corresponding to 45 PVs in Fig. 10 had a minimum of 20 wind turbines corresponding to a minimum total investment cost of 2×10^5 € (see a small circle in Fig. 10). The obtained point is the same as the one obtained in Fig. 9. This configuration (20 WTs and 45 PVs) may not correspond to the optimal investment cost for any storage capacity because it depends on the size of the battery bank. If an investor wants more autonomy, searching for another suitable optimal configuration is necessary.

The storage capacity size (i.e., the number of batteries) is a critical factor in the economic evaluation of such systems because of their high price. Therefore, a simulated investment cost function versus the number of PV panels and wind turbines was calculated, corresponding to 48 batteries that fit an autonomy duration of one day. For this level of storage capacity, a 3D curve plot was generated for a total investment cost (€) as a function of wind turbines and the number of PV panels (Fig. 11). This 3D curve showed a minimum in the overall investment cost. The optimal number of photovoltaic generators ranged between 51 and 61 PV panels (see close-up in upper RHS of Fig. 11). The optimal number of wind turbines ranged between 9 and 14 WTs. The best combination for the hybrid scheme for a one-day autonomy (i.e., corresponding to a storage capacity that covers the energy needs for one day) suggests a system with 61 PV panels and 9 wind turbines.

This project was a reduced-scale system financed from the company's budget, so the discount rate was zero. The Levelized cost of energy (LCOE) was calculated since it is a fundamental metric in deciding whether to move forward with the project. The investment cost was determined to be 266,763€ for the best configuration of the hybrid system. When divided by the total electricity generation over its lifetime, it led to a levelized cost of energy of 0.2388€ per kWh. This value was relatively high because it depended on the system generator's rated power and the autonomy duration.

Furthermore, the Hydrocarbons Regulatory Authority controlled the national electricity and fuel market by setting predefined prices in the

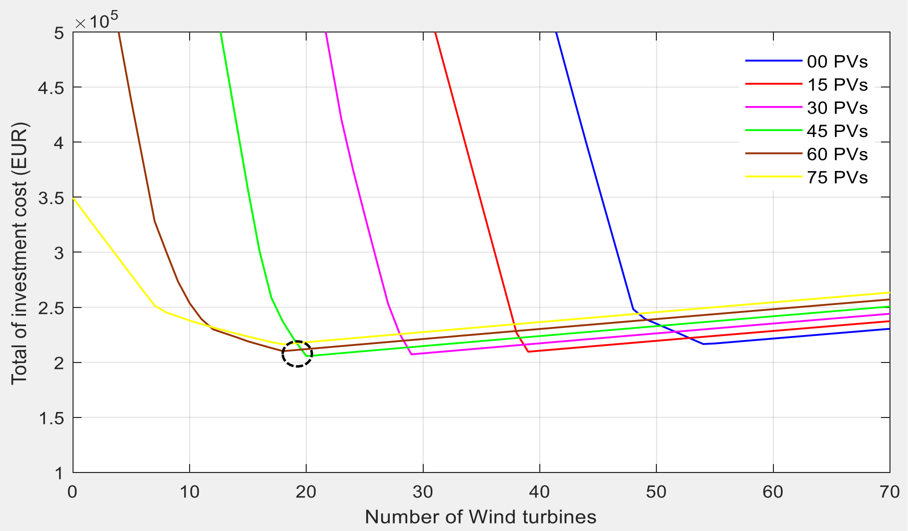

Fig. 10. Investment cost as a function of number of wind turbines for various constant number of photovoltaic panels ranging from 0 to 75 PVs.

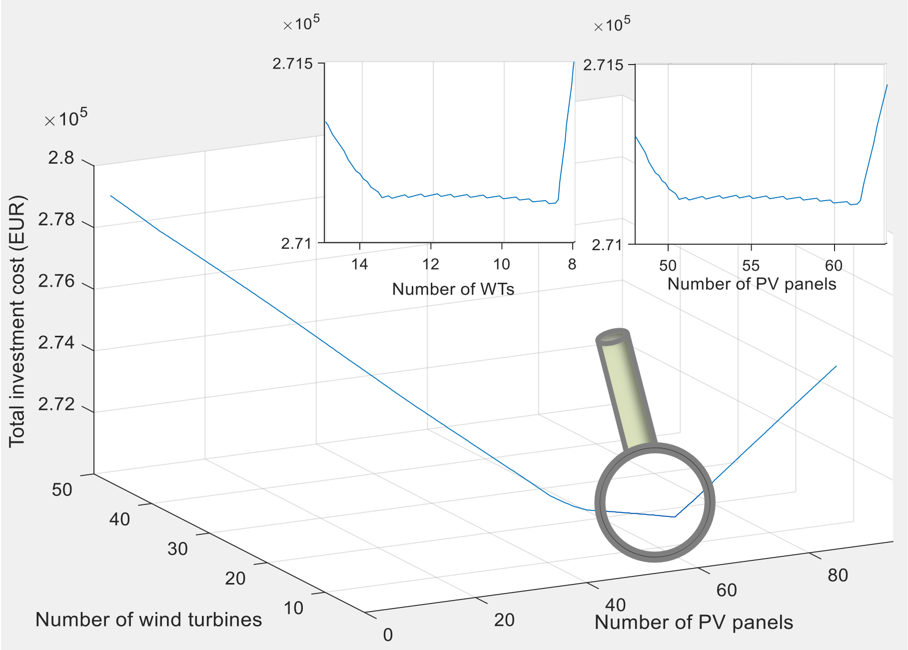

Fig. 11. 3D curve plot of investment cost as a function of number of wind turbines and PV panels.

case study region. These tariffs were given by power level and according to the annual duration of use ranging from 4.1789 DA (around 0.0209€) to 5.4796 DA (around 0.0274€) per kWh. The resultant cost of energy was very high and not attractive to companies. But it remained within the standard prices when compared to European countries. A technical report published by the Fraunhofer Institute for Solar Energy Systems in 2021 noted that the LCOE for PV battery systems currently ranges between 0.0524 and 0.1972 €/kWh. This wide range resulted from cost differences for battery systems (i.e., 500 to 1200 €/kWh) in combination with cost differences for PV systems and varying solar irradiation levels [37].

The investment cost of each component of the hybrid system was also analyzed. Based on a levelized cost of energy analysis, the batteries accounted for 85% of the total investment cost (Fig. 12). The PV panels accounted for 10%, and the wind turbines for only 3% of the total cost. The bank of batteries took the major share of the hybrid system budget.

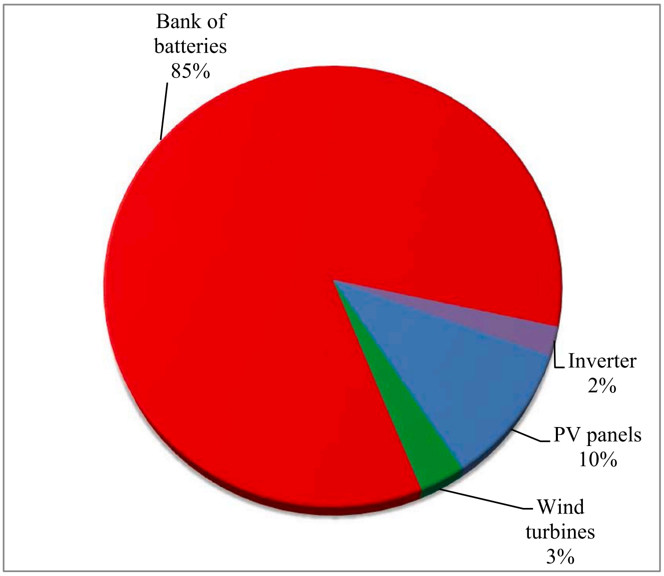

Fig. 12. The pie chart of investment cost (case of one day autonomy).

Energy storage is a common feature in most PV systems that are not connected to the utility grid (i.e., off-grid). Based on the current study, battery costs were a substantial fraction of the total cost of the hybrid system. One decided to have a lower storage capacity of the battery bank (i.e., fewer batteries) to reduce the investment cost and the high LCOE. The storage capacity was reduced to a third, corresponding to 16 batteries and an autonomy duration of 8 h. The investment cost was again simulated as a function of the number of PV panels and wind turbines (Fig. 13) to find the optimal configuration for this storage capacity. The plot of the 3D curve of the investment cost function shows that it has a restricted area where we can easily pull the number of PV panels and the number of wind turbines corresponding to the optimal cost.

In this case, the optimum number of wind generators was 65 WTs, and the number of photovoltaic generators was 11 PV panels. The energy cost was reduced to 0.1301€ per kWh, compared to 0.2388€ per kWh, which was a very competitive price for European countries (i.e., 0.1972 €/kWh). It should be noted that by changing the autonomy from 24 to 8 h, the investment cost for the battery storage system share was reduced, and the wind turbine share was increased compared to the first case (Figs. 12 and 14). However, this price remained uncompetitive despite the significant reduction in energy cost brought by a decrease in the number of batteries. It did not encourage private investment in the case study region. The energy cost of the public grid was around 0.0209€ per kWh, which was still six times less due to the government's widely available and heavily subsidized fossil resources.

It is important to remember that hybrid systems such as solar PV and wind comprising more than one energy supply and a storage system offer a fitting solution to deal with the intermittent nature of renewable resources [38]. In this regard, north African countries such as Algeria have enormous potential, particularly in solar energy [38,39]. The present investigation shows that photovoltaic and wind hybrid systems can be economically viable alternative energy sources. Adding a storage capacity improves the system's efficiency and the power supply's reliability. However, as supported by the current results, unnecessary oversizing some elements, such as storage batteries, can lead to additional costs [12]. Therefore, optimizing simulation models for hybrid system sizing can effectively reduce production costs, as shown by this investigation.

Despite tremendous improvements in generation, most of the world's

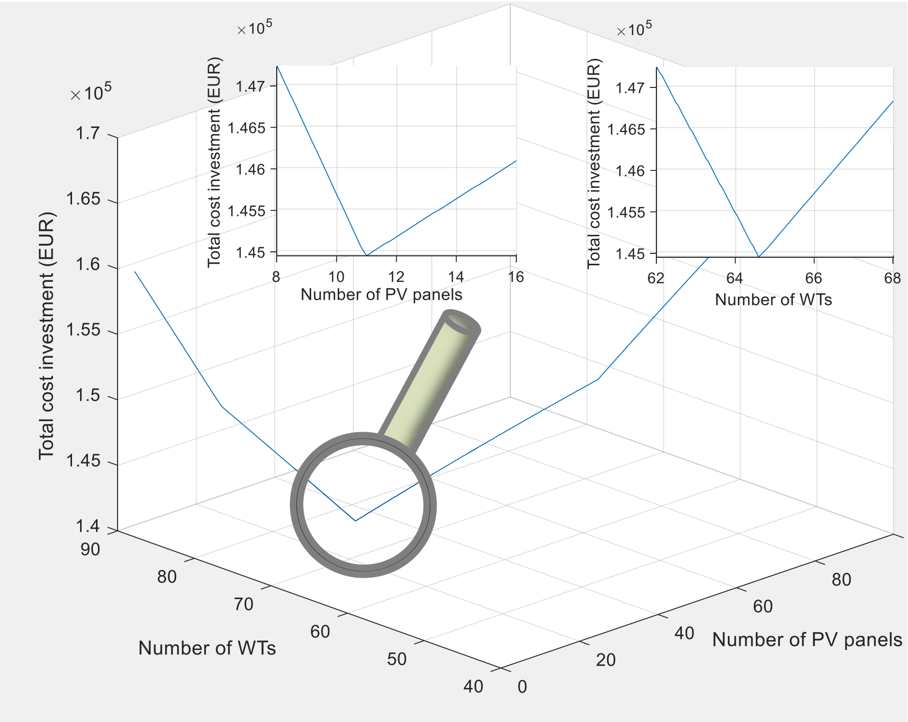

Fig. 13. Investment cost VS number of wind turbines and number of PV panels assuming 8 h of autonomy duration.

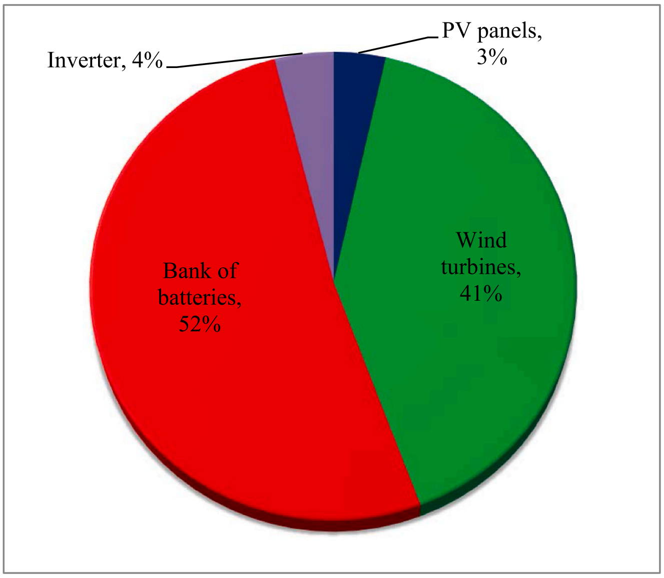

Fig. 14. The pie chart of investment cost (case of 8 h autonomy duration).

population, especially in Africa, continues to experience poor access to electricity [1,38]. Most of these developing countries' infrastructures are centralized grid-connected power systems, making it difficult for areas far from the grid to access a sustainable power supply. Authors of [1] reported on a performance evaluation of a hybrid power system for sustainable electricity generation using a case study from Sierra Leone's Southeastern region. They concluded that the preference of governing authorities would determine which optimal design would be chosen. By following this strategy, the authors argued that an optimal scenario could lead to a long-term power supply and provide cost-effective electricity for the region. This report is somewhat like the problems of the current case study site in Algeria: government decision-making in providing subsidies for electricity generation from fossil fuels inhibits the development of renewable energy technology. Related research by Ref. [40] applied a decision-making process based on a government initiative to undertake a project to provide sustainable electricity to the same region with the financial assistance of the Africa Development Bank (ADB) and the Department for International Development (DFID). The findings of their investigation showed that an optimized hybrid configuration performed best in terms of technical, economic, and environmental aspects. This was like the present investigation, where a combination of technical and financial analysis was combined to give an optimum hybrid configuration. Likewise, the authors of [2] examined optimal combinations of a wind farm by using a mixed-integer linear programming model and evaluated a wind farm transformer using a dynamic transformer rating. Based on a sensitivity analysis, the authors concluded that wind resources and electricity prices were critical parameters for the wind farm's feasibility. This contrasted with the current study, where the critical economic parameter was the number of storage batteries.

4. Conclusions

The analysis of meteorological data and the load taken at the study site revealed a significant renewable energy potential for the region. The technical simulation model analysis demonstrated that the storage capacity (i.e., number of batteries) greatly influenced the size of the other components. Configurations obtained by the technical analysis meet the requirement that the probability of loss of power supply is zero, which makes these configurations may be oversized and not optimal. The economic study demonstrated that energy storage (i.e., the number of batteries) occupies the most crucial part of the total investment cost of the hybrid system. With 48 batteries of storage system corresponding to complete autonomy of one day (i.e., storage capacity that covers the energy needs for one day), the best combination for the hybrid scheme was a system with 61 PV panels and 9 wind turbines. For this combination, the batteries bank took a significant share (85%) of the hybrid system budget, leading to a high levelized cost of energy. By changing the autonomy from 24 to 8 h, only 16 batteries were required, along with 11 PV panels and 65 wind turbines. Based on a levelized cost of energy analysis, the batteries accounted for the last combination is 51% of the total investment cost. The wind turbines accounted for 41%, and the PV panels for only 3% of the price. This combination of the hybrid system resulted in an energy cost that was competitive with most European countries and had zero greenhouse gas emissions. However, the cost of the public energy grid in the case study region was still six times lower due to government subsidies, and thus it can be argued as not sustainable. This inhibits the development and deployment of renewable resources, especially in the private sector. Future research should look at alternative energy storage systems, such as thermal microturbines, which are more reliable and competitive. Enhanced environmental analysis is also required to reduce further overall greenhouse gas emissions as well as the cost of energy.

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Credit author statement

Abdelfettah Kerboua: Conceptualization, Methodology, Formal analysis, Investigation, Software, Resources, Writing - Original Draft; **Fouad Boukli Hacène:** Conceptualization, Methodology, Formal analysis, Data Curation; **Mattheus F.A. Goosen:** Conceptualization, Validation; **Luis Frölén Ribeiro:** Conceptualization, Writing - Review & Editing, Visualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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