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Deterministic Optimization and Cost Analysis of Hybrid PV/Wind/Battery/Diesel Power System

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Abstract- This paper focuses on the development of a deterministic approach for optimum sizing of the hybrid power systems (PV/wind/battery/diesel and PV/wind/diesel) based on the DIviding RECTangles (DIRECT) algorithm, which can attain the optimum values of commercially available system devices ensuring that the system total investment cost is minimized while guaranteeing the electricity requirements of the customers and the safety of the system. The hybrid power systems are assumed to be installed at an Experimental Remote Ecological Area (EREA), France, with 5-year period of average hourly data (solar radiation, wind speed, ambient temperature and electrical power demand of the load). Finally, the optimum values obtained of the system components during a period of 20-year are obtained including the number of PV modules, the PV module surface area, the number of wind turbines, the wind turbine installation height, the battery bank number and the diesel generator operating hours with their lowest system total investment costs. Additionally, a detailed analysis of the System Total Investment Cost (STIC), structure of the hybrid PV/wind/battery/diesel power system and an impact of optimum system configuration on system performance are compared and discussed in the case studied.

Keywords- Detailed cost analysis; DIRECT algorithm; Hybrid power system; Optimization; PV; STIC; wind turbine.

1. Introduction

The energy produced by conventional energy sources results in increased greenhouse gas emissions which, if not drastically reduced, threaten the global climate's stability [1]. For this reason, the generation of electrical energy through the use of alternative sources such as wind and solar, have become more attractive and they are widely used for substituting fossil fuels in the process of electrical power energy generation since 1970s because of the crisis oil [2]. Such alternative energy sources are expensive in their investment costs. The hybrid power system which includes alternative energy sources with diesel generators and energy storage requirements often has a lower cost than the system which has only one of the above alternative source.

A large number of optimization methodologies have been used for hybrid power systems' technical-economic feasibility. A probabilistic approach based on the loss of power supply probability method was suggested by Yang et al. [3]. In this paper, the optimum number of PV modules and optimum capacity of wind turbine for the desired loss of power supply probability with different battery storage capacities were achieved for a period of 1 year climatic data called typical meteorological year. Tina et al. [4] presented a probabilistic approach based on the convolution technique to assess the long-term performance for a hybrid solar-wind power system by use of the energy index for reliability for both stand-alone and grid-linked applications. The probabilistic model developed in this paper is further modified in [5] including the PV panel tracking system (one and two-axis tracker) on the probability density function of the power produced. An impact and a reliability analysis of the tracking system on the proposed hybrid system were estimated.

A stochastic approach based on the genetic algorithm for stand-alone hybrid solar-wind system with battery storage was recommended by Yang et al. [6,7]. This optimization model is used to calculate the optimum system configuration which can achieve the desired loss of power supply probability with minimum annualized cost of system. Cabral et al. [8] portrayed a methodology to stochastically analyze the size of stand-alone photovoltaic systems. A stochastic program is developed for the calculation of photovoltaic generators and batteries for a given load. The obtained results were compared with those for sizing of stand-alone photovoltaic-battery system using the Sandia deterministic method.

In deterministic approaches, the renewable energy resources and the demand are considered as deterministic quantities and their variation with respect to time is assumed to be known [9]. Belfkira et al. [10] presented a deterministic approach for optimal sizing of wind-PV-diesel system with batteries and wind-PV-diesel system without batteries with hourly data environment for a period of 6-month in the area of Dakar. The results obtained show that the diesel generator operating hours can be reduced by using the battery banks. The deterministic approach is seen to be potentially much faster than recently developed algorithms based on evolutionary optimization algorithms [11].

However, the collection of the environment data in all above methods described is not enough to enhance the performance and the reliability of the optimal hybrid power system for a long-term period. The aim of this paper is to present a methodology helping to perform the techno-economic feasibility studies of hybrid power systems supplying the electrical power demand of residential loads (buildings) at an Experimental Remote Ecological Area (EREA), France. A long-term average hourly data of 5-year period is used to optimize the sizing of the hybrid system components resulting in the lowest system total investment costs.

The present paper is structured in 5 sections. In section 1, the mathematical model of the system components consisting of the PV module, the wind turbine, the battery bank and the diesel generator is developed. Section 2 proposes an hourly operational strategy for a hybrid PV/wind/battery/diesel power system. In section 3, a deterministic optimization approach is developed by using the DIRECT algorithm in order to optimize the sizing of the system components. In section 4, the proposed deterministic optimization approach is applied to the EREA in order to find the optimum system configuration by minimizing the system total cost for a period of 20-year. A detailed analysis of the system total investment cost structure and the impact of optimum system configuration on system performance are presented and discussed in this section. Finally, section 5 summarizes the conclusions.

2. Mathematical model of hybrid power system

2.1. Description of hybrid power system configuration.

The proposed hybrid PV/wind/battery/diesel power system configuration in this study is shown in Fig. 1. In this configuration, the PV module, the wind turbine, the battery bank and the diesel generator are paralleled in order to meet the electrical power demand of the load. Since the output power of the PV module and the wind turbine is intermittent due to the climatic conditions and the necessity to provide the constant power supply to the load side, a group of battery banks is required as an energy storage system. The excess power generated by the PV module and the wind turbine is stored in the battery bank until full capacity of the storage system is reached. Once the power is deficit, the battery bank will discharge to supply the shortfall in load demand. The diesel generator is operated when the PV module and the wind turbine fail to satisfy the electrical power demand and when the battery bank is depleted. In order to guarantee the inverter working normally, the system loads also include a dump load for consuming the surplus power generated by the hybrid system.

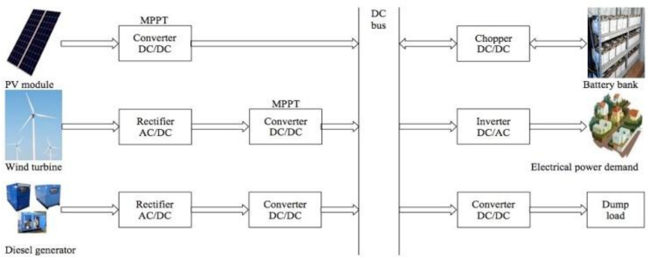

Fig. 1. Block diagram of the hybrid power system.

2.2. Mathematical model of PV module system

PV module is an interconnected assembly of the PV cells and is the basic component of a PV system. The PV module performance is affected by the environmental conditions such as the solar radiation, the ambient temperature and the characteristics of the PV cells under the industrial standard test conditions of solar radiation of 1000 W/m2 with zero angle of incidence, solar spectrum of 1.5 air mass and 25 °C cell temperature. In this section, the Maximum Power Point Tracker (MPPT) holds all the PV modules at their respective maximum power points for calculating the hourly optimum operating point current ($I_{PV,max}(t)$) and voltage ($V_{PV,max}(t)$) which are given by Belfkira et al. [10] and Ai et al. [12]. The hourly output power of a single PV module at the maximum power point ($P_{PV,max}(t)$) is given by the following equation:

$$P_{PV,\max}(t) = I_{PV,\max}(t) \times V_{PV,\max}(t) \tag{1}$$

A PV system consists of a number of individual PV modules that have been wired together in series and/or in parallels to deliver the voltage and the amperage that a particular system requires. The PV modules are connected in parallel to increase the current and in series to produce a higher voltage. The total number of the PV modules (N_{PV}) can be written as:

$$N_{PV} = N_{PV,s} \cdot N_{PV,p} \tag{2}$$

where $N_{PV,s}$ and $N_{PV,p}$ are the number of PV modules in series and in parallel. $N_{PV,s}$ can be determined by the selected DC bus voltage (Vbus) and the nominal voltage of the PV module (VPV,nom) as the following equation (3). $N_{PV,p}$ is the design variable of the system in this paper.

$$N_{PV,s} = \frac{V_{bus}}{V_{PV,nom}} \tag{3}$$

The total surface area of the PV modules (S_{PV}) is another important parameter in the PV module system. It can be calculated according to the following equation:

$$S_{PV} = A_{PV} \cdot N_{PV} = A_{PV} \cdot N_{PV,s} \cdot N_{PV,p} \tag{4}$$

where A_{PV} is the total surface area of a single PV module in the system.

The total hourly output power of the PV modules ($P_{PV(t)}$) can be calculated by:

$$P_{PV}(t) = N_{PV} \cdot P_{PV,\max}(t) \tag{5}$$

2.3. Mathematical Model of Wind Turbine System

The wind turbine system, starting with the description of the wind speed, is presented in this section. The wind speed at its tower height can be calculated by using the power law equation as follows [13]:

$$v(t) = v_r(t) \cdot \left(\frac{h}{h_r}\right)^{\gamma} \tag{6}$$

where $v(t)$ is the hourly wind speed at the desired height h, $v_r(t)$ is the hourly wind speed at the reference height hr and γ is the power law exponent ranging from 1/7 to 1/4 [13]. The tower height of the wind turbine is an important factor which significantly influences the operating performance of the wind turbine. It can also be well over half the cost of the wind turbine system overall.

In this paper, the hourly output power of the wind turbine ($P_{WT}(t)$) can be determined as [10]:

$$P_{WT}(t) = \begin{cases} a.v^3(t) - b.P_r, & v_{ci} < v < v_r \\ P_r, & v_r < v < v_{co} \\ 0, & otherwise \end{cases} \tag{7}$$

Where

$$a = \frac{P_r}{v_r^3 - v_{ci}^3} \tag{8}$$

$$b = \frac{v_{ci}^3}{v_r^3 - v_{ci}^3} \tag{9}$$

where v_{ci}, v_r and v_{co} are the cut-in wind speed, rated wind speed and cut-off wind speed. P_r is the rated power.

2.4. Mathematical Model of Battery Bank System

The difference in power generated between the renewable energy sources and the electrical power demand, determines whether the battery bank is in charging or discharging state. During the charging process and discharging process of the battery bank, the battery State Of Charge *(SOC)* at the hour *t (SOC(t))* is evaluated by the following equation [13,14]:

$$SOC(t) = SOC(t-1) \cdot \left(1 - \delta_{bat}(t)\right) + \left(\frac{P_B(t)}{V_{bus}}\right) \cdot \eta_{bat} \cdot \Delta t \tag{10}$$

The value of $SOC(t)$ could not be lower than its allowable minimum limit (SOC_{min}), and it could not be higher than its allowable maximum limit (SOC_{max}) during charging operation. These conditions are considered the constraints under the battery banks operation:

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \tag{11}$$

For longevity of the battery bank, the maximum charging rate (SOC_{max}) is given as the upper limit, and it takes the value of the total nominal capacity (C_n) of the battery bank which is defined by the total number of battery banks (N_{BAT}), the number of series connected of battery banks ($N_{BAT,s}$) and the nominal capacity of each individual battery ($C_{BAT,nom}$) as follows [15]:

$$SOC_{\max} = C_n = \frac{N_{BAT}}{N_{BAT,s}} \cdot C_{BAT,nom} \tag{12}$$

The battery banks are connected in series to give the desired nominal DC operating voltage (V_{bus}) and are connected in parallel to yield a desired system storage capacity. Thus, the number of battery banks connected in series ($N_{BAT,s}$) depends on the DC bus voltage (V_{bus})and the nominal voltage of each individual battery ($V_{BAT,nom}$). It is given by:

$$N_{BAT,s} = \frac{V_{bus}}{V_{BAT,nom}} \tag{13}$$

The number of the battery banks for parallel connection ($N_{BAT,p}$) which determines the capacity of the battery bank is the design variable of the system in this study. The total number of the battery banks (N_{BAT}) can be determined by:

$$N_{BAT} = N_{BAT,s} \cdot N_{BAT,p} \tag{14}$$

The minimum permissible state of charge (SOC_{min}) of the battery bank during discharging may be expressed as the following equation:

$$SOC_{\min} = (1 - DoD) \cdot SOC_{\max} \tag{15}$$

where *DoD* is the maximum Depth of Discharge.

2.5. Diesel Generator System

Diesel generator system design simply involves selecting a locally available unit that is closest to the peak load requirements of the application. Where, the diesel generator operates most efficiently when running between 80-90% of its rated power and become less and less efficient as the load decreases [16]. The rated power *($P_{D,rated}$)* of the diesel generator should be at least equal to the peak load demand *(P_{pload})* as follows:

$$P_{D,rated}(t) \geq P_{pload}(t) \tag{16}$$

The fuel consumption of the diesel generator at no load is almost 30% of the corresponding fuel consumption at the rated power. Thus, it is recommended to avoid the diesel generator operation below 30% of full load for long periods, in order to avoid serious maintenance problems, like chemical corrosion and glazing [17].

3. Hourly Operational Strategy

An hourly operational strategy is proposed to deal with the paradox of the alternating supply and the demand excesses. A flowchart of the proposed operational strategy for the hybrid power system is shown in Fig. 2.

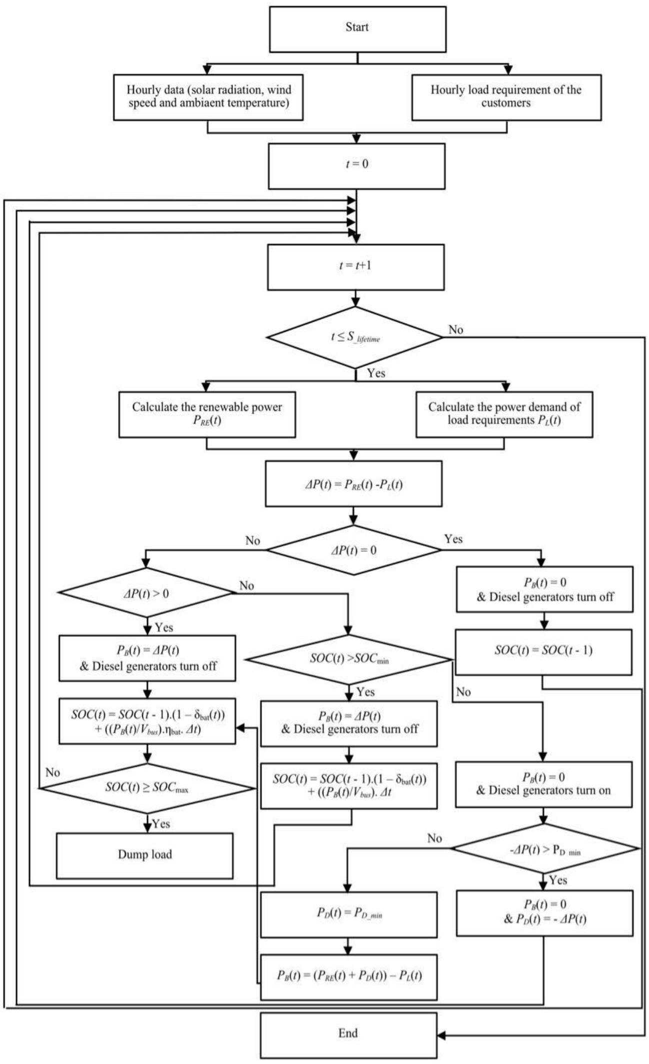

Fig. 2. Flowchart of operational strategy for the hybrid power system.

It is explained in the following step:

1) If ΔP is equal to zero, the battery banks is neither charged nor discharged and the SOC of the battery banks depends on the previous value at the time *t* during the equilibrium power between the renewable sources and the load requirements. The diesel generators are turned off.

2) If the value of ΔP is positive, the remaining surplus power will be used to charge the battery banks until the *SOC* of battery banks reaches its maximum value *(SOC_{max})* and the diesel generators are turned off. The excess power is dumped.

3) If ΔP falls below zero, the remaining surplus power will be given by the battery banks or by the diesel generators, depending on the dispatch strategy:

i. If the *SOC* of the battery banks is larger than its minimum value *(SOC_{min})*, the battery banks discharges ΔP and the diesel generators are turned off.

ii. If the *SOC* of the battery banks decreases to its minimum value *(SOC_{min})*, the battery banks will be neither charged nor discharged and the diesel generators are activated to meet the electrical power demand. In this situation, if ΔP is larger than the minimum value of the diesel generators *(P_{D_min})*, it will be given by the diesel generators. Contrarily, the diesel generators run at its minimum value *(P_{D_min})* and the remaining surplus power is charged to the battery banks.

4. Optimization technique

In order to efficiently and economically utilize the renewable energy resources, an optimum sizing method is necessary. In this paper, a deterministic global optimization algorithm, namely Dividing RECTangles (DIRECT), is presented with sufficient details and applied to find the optimum solution which minimizes the System Total Investment Cost (STIC) subject to the constraints of the hybrid system components.

4.1. Description of DIRECT Algorithm

The DIRECT algorithm, developed by Jones et al. [18], was proposed in order to solve the global minimum of a multivariate function subject to bound-constrained domains. DIRECT deal with the following optimization problem [10,19]:

$$\min_{x \in \Omega} f(x) \tag{17}$$

where

$$\Omega = \left\{ x \in \mathrm{R}^N \middle| l_i \leq x_i \leq u_i \right\} \tag{18}$$

$f: \mathbb{R}^N \rightarrow \mathbb{R}$, is the objective function which has been subjected to the following constraints:

$$\begin{cases} h(x) = 0 \\ g(x) \geq 0 \end{cases} \tag{19}$$

where h : $\mathbb{R}^P \to \mathbb{R}$ and g : $\mathbb{R}^Q \to \mathbb{R}$ are the equality and the inequality constraints.

The DIRECT algorithm is applied to optimize the sizing of the system components ensuring that the system total investment cost is minimized subject to the different constraints of the hybrid system components. The objective function and the constraints are formulated in the next subsections.

4.2. Objective function

The objective function taken here is to minimize the System Total Investment Cost (STIC) during the system lifetime ($S_{\_lifetime}$). The STIC is composed of the capital cost ($C_{\_ins}$), the installation cost ( ), the annualized Operation and Maintenance (O&M) cost ($C_{\_O\&M}$), the replacement cost ($C_{\_rep}$) of the PV modules, the wind turbines and the battery banks and the operation cost of the diesel generators ($C_{\_Diesel}$) throughout the system lifetime. In this study, the replacement cost of the battery banks is considered equal to the sum of their capital cost and installation cost. However, other cost components, such as inverter cost, rectifier cost, cable cost and control system cost, usually accounts only for a minor share of the STIC and, are not considered in this study. The objective function of the STIC can be given by the following equation [14,20]:

$$\min_x STIC(x) = \min_x \left[C_{\_cap}(x) + C_{\_ins}(x) + C_{\_O\&M}(x) + C_{\_rep}(x) + C_{\_Diesel}(x) \right] \tag{20}$$

where $x = \left(N_{PV}^i, N_{WT}^j, N_{BAT}^k, S_{PV}^i, H_{WT}^j \right)$, is the vector of the sizing variable. N_{PV}^i , N_{WT}^j and N_{BAT}^k are the total number of the PV modules of model i , the total number of the wind turbines of model j and the total number of the battery banks of model k . S_{PV}^i is the total area of the buildings' rooftops which have been integrated with the PV modules of model i and H_{WT}^j is the tower height of the wind turbines of model j.

More detailed form of the STIC function is expressed in the following equation:

$$\begin{aligned} & STIC\left(N_{PV}^i, N_{WT}^j, N_{BAT}^k, H_{WT}^j\right) \\ & = \sum_{i=1}^{n_{PV}} N_{PV}^i \cdot \left(C_{\_cap,PV}^i + C_{\_ins,PV}^i + S_{\_lifetime} \cdot C_{\_O\&M,PV}^i + R_{PV}^i \cdot C_{\_rep,PV}^i \right) \\ & + \sum_{j=1}^{n_{WT}} N_{WT}^j \cdot \begin{bmatrix} C_{\_cap,WT}^j + C_{\_ins,WT}^j + H_{WT}^j \cdot \left(C_{\_cap,T}^j + C_{\_ins,T}^j \right) \\ + S_{\_lifetime} \cdot \left(C_{\_O\&M,WT}^j + C_{\_O\&M,T}^j \right) + R_{WT}^j \cdot C_{\_rep,WT}^j \end{bmatrix} \\ & + \sum_{k=1}^{n_{BAT}} N_{BAT}^k \cdot \begin{bmatrix} C_{\_cap,BAT}^k + C_{\_ins,BAT}^k + \left(S_{\_lifetime} - R_{BAT}^k - 1 \right) \cdot C_{\_O\&M,BAT}^k \\ + R_{BAT}^k \cdot \left(C_{\_cap,BAT}^k + C_{\_ins,BAT}^k \right) \end{bmatrix} \\ & + C_{\_Diesel} \end{aligned} \tag{21}$$

where R_{PV}^i , R_{WT}^j and R_{BAT}^k are the number of times of the PV modules of model *i*, the number of times of the wind turbines of model *j* and the number of times of the battery banks of model *k* will be replaced over the system lifetime.

The calculation of operation cost of the diesel generators can be determined as follows [14,20]:

$$C_{\_Diesel} = C_{\_ins,D} + C_{\_O\&M,D} + \frac{C_{\_aqu,D}}{D_{\_lifetime}} + C_{\_fuel,D} \tag{22}$$

where $C_{\_ins,D}$, $C_{\_O\&M,D}$ and $C_{\_aqu,D}$ present the installation cost of the diesel generators, the diesel generators hourly O&M cost and the diesel generators acquisition cost. $D_{\_lifetime}$ is the diesel generator lifetime and $C_{\_fuel,D}$ is the cost of the fuel consumed by the diesel generators.

Diesel generator has typically a maximum fuel efficiency of about 3 kWh/l when run above 80% of its rated capacity. When diesel generator is run at loads below 30% of its rating, the fuel efficiency becomes very low [21]. Eq. (23) shows the fuel consumption cost for 1 h of running of the diesel generator [22]:

$$C_{\_fuel,D} = \mathrm{Pr}_{\_fuel} \cdot \left(A \cdot P_D + B \cdot P_{D,rated} \right) \tag{23}$$

where $Pr_{\_fuel}$ is the fuel price, A = 0.246 l/kWh and B = 0.0845 l/kWh are the fuel curve coefficients.

Another interesting function in this paper is the System Initial Equipment Cost (SIEC), which is defined as follows:

$$\begin{aligned} & SIEC\left(N_{PV}^i, N_{WT}^j, N_{BAT}^k, H_{WT}^j\right) \\ & = \sum_{i=1}^{n_{PV}} N_{PV}^i \cdot \left(C_{\_cap,PV}^i + C_{\_ins,PV}^i + C_{\_O\&M,PV}^i / S_{\_lifetime} \right) \\ & + \sum_{j=1}^{n_{WT}} N_{WT}^j \cdot \begin{bmatrix} C_{\_cap,WT}^j + C_{\_ins,WT}^j + H_{WT}^j \cdot \left(C_{\_cap,T}^j + C_{\_ins,T}^j \right) \\ + \left(C_{\_O\&M,WT}^j + C_{\_O\&M,T}^j \right) / S_{\_lifetime} \end{bmatrix} \\ & + \sum_{k=1}^{n_{BAT}} N_{BAT}^k \cdot \begin{bmatrix} C_{\_cap,BAT}^k + C_{\_ins,BAT}^k \\ + C_{\_O\&M,BAT}^k / \left(S_{\_lifetime} - R_{BAT}^k - 1 \right) \end{bmatrix} \\ & + C_{\_Diesel,per} \end{aligned} \tag{24}$$

4.3. System Constraints

The minimization of the objective function is formulated corresponding to the following system constraints:

1) The hourly power produced by the diesel generators (PD(t)) maybe equals to zero or any value between 30% of rated power (0.3·PD,rated) and 100% of rated power (PD,rated) as follows:

$$\begin{cases} P_D(t) = 0 \\ 0.3 \cdot P_{D,rated} \le P_D(t) \le P_{D,rated} \end{cases} \tag{25}$$

2) The hourly SOC of the battery banks is limited between SOCmin and SOCmax as follows:

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \tag{26}$$

3) The hourly power produced by the hybrid power system (PP(t)) is equal to the electrical power demand(PL(t)) as follows:

$$P_P(t) = P_L(t) \tag{27}$$

4) The additional constraints of system components limits are given by:

$$\begin{cases} 0 \le N_{PV,p}^{i} \le N_{PV,p\max}^{i} \\ 0 \le N_{WT}^{j} \le N_{WT,\max}^{j} \\ 0 \le N_{BAT,p}^{k} \le N_{BAT,p\max}^{k} \\ 0 \le S_{PV}^{i} \le S_{PV,\max}^{i} \\ H_{WT,\min}^{j} \le H_{WT}^{j} \le H_{WT,\max}^{j} \end{cases} \tag{28}$$

where $N_{PV,p\max}^{i}$, $N_{WT,\max}^{j}$ and $N_{BAT,p\max}^{k}$ are the maximum number of the PV modules of model i, the maximum number of the wind turbines of model j and the maximum number of the battery banks of model k and are calculated according to the nominal power of the PV modules, the nominal power of the wind turbines, the nominal capacity of the battery banks and the peak power of load demand. $S_{PV,\max}^{i}$ is the maximum surface area of the PV modules of model i. $H_{WT,\min}^{j}$ and $H_{WT,\max}^{j}$ are the tower height limits respectively.

Therefore, the model for the optimization of the proposed hybrid power system is expressed as follows:

$$\min_{x} STIC(x) \tag{29}$$

subject to:

$$\begin{cases} P_P(t) = P_L(t) \\ 0.3 \cdot P_{D,rated} \le P_D(t) \le P_{D,rated} \\ SOC_{\min} \le SOC(t) \le SOC_{\max} \\ 0 \le N_{PV,p}^{i} \le N_{PV,p\max}^{i} \\ 0 \le N_{WT}^{j} \le N_{WT,\max}^{j} \\ 0 \le N_{BAT,p}^{k} \le N_{BAT,p\max}^{k} \\ 0 \le S_{PV}^{i} \le S_{PV,\max}^{i} \\ H_{WT,\min}^{j} \le H_{WT}^{j} \le H_{WT,\max}^{j} \end{cases} \tag{30}$$

4.4. Optimization Procedure

The optimization procedure aims to solve the above optimal problem described. In the flowchart of the proposed optimization procedure, which is shown in Fig. 3, i is the number of the iteration.

5. Case study

5.1. Input Data of EREA

A community consisted of around 150 individual residential buildings, considered as an Experimental Remote Ecological Area (EREA), is situated 10km from the city of Le Havre, France. This EREA has almost the same geographical coordinates as Le Havre, defined as: latitude 49°30¢32²N, longitude 00°04¢16²E and average altitude 53 m above sea level.

5.1.1. Electrical power demand of EREA

In order to estimate the electrical power consumption of the EREA, the average hourly electrical power demand of a similar area to the EREA is measured and collected for a period of 5-year which from 1st January 2006 to 31th December 2010 in Fig. 4. It is important to note the increase of the electrical power consumption during the 5 years of the measured data and on can observe a peak electrical power demand of 290 kW at the at 15th December 2010.

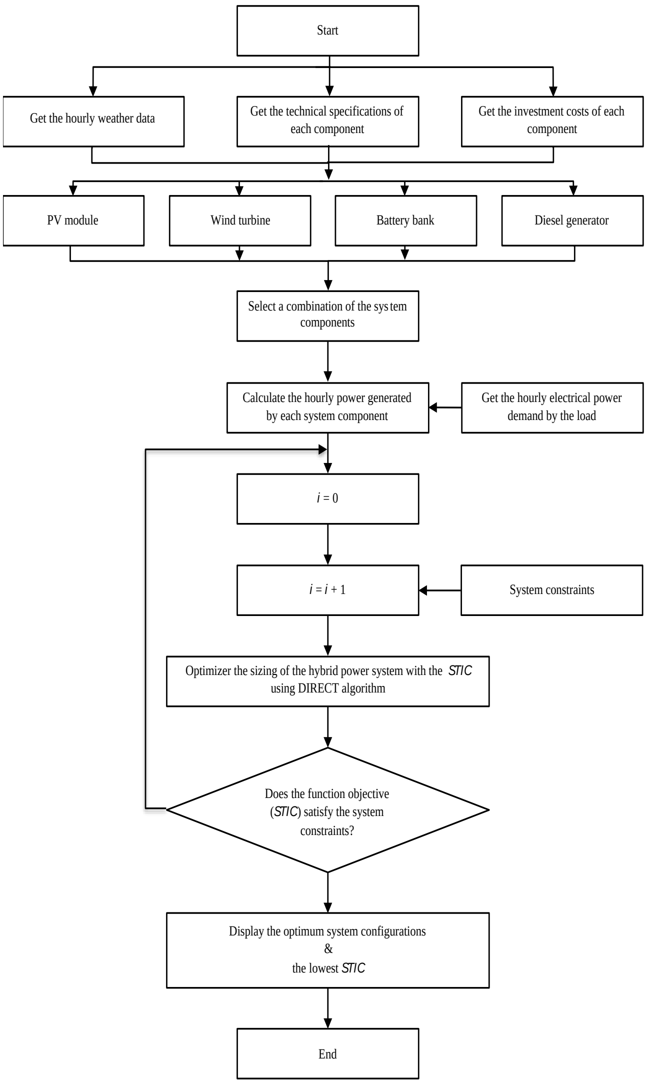

Fig. 3. Flowchart of the proposed optimization procedure.

5.1.2. Climatic Conditions of EREA

In order to satisfy the increasing electric consumption demand, the generation of electrical power by means of renewable energy resources and alternative energy sources such as solar energy, wind energy as well as diesel generators has been considered as the best choice of the EREA which is blessed with the similar meteorological data of Le Havre. The measured data of the average hourly solar radiation, the average hourly wind speed and the average hourly ambient temperature of Le Havre for a period of 5-year which run from 1st January 2006 to 31th December 2010 are used and plotted in Figs. 5-7. It is noted that the EREA has almost similar solar radiation and quite different wind speed during the whole 5 years.

In this context two hybrid power systems (PV/wind/battery/diesel and PV/wind/diesel), considered as the stand-alone hybrid systems, are assumed to be installed in proximity of the EREA by providing sustainably the electrical power demand for the inhabitants of this remote community.

5.1.3. Specifications and Investment Costs of System Components

Four different commercial models of PV modules, battery banks and wind turbines are proposed in this study. The library of system components can be enhanced in the future. Their specifications and the investment costs are listed in Tables 1-3. It can be noticed form Tables 1 and 2, that the capital costs have dominated the system total investment costs.

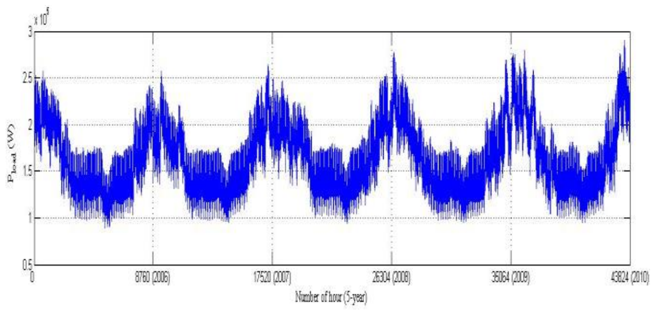

Fig. 4. Average hourly electrical power demand of EREA for a period of 5-year.

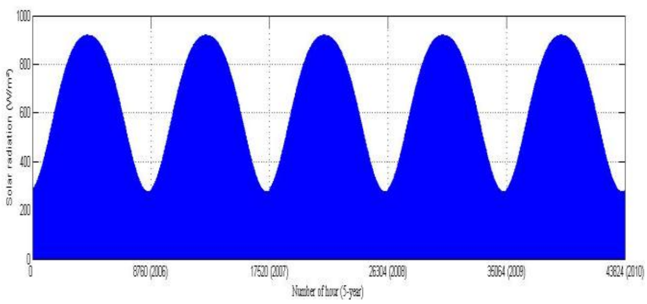

Fig. 5. Average hourly solar radiation of EREA for a period of 5-year.

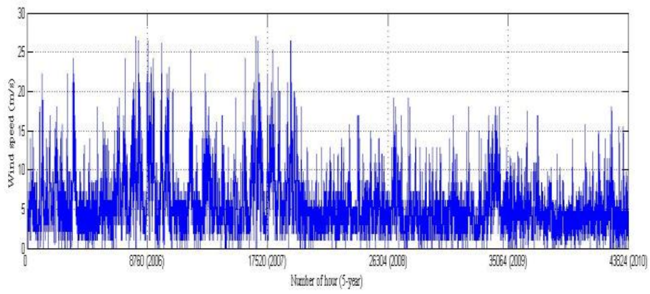

Fig. 6. Average hourly wind speed of EREA for a period of 5-year.

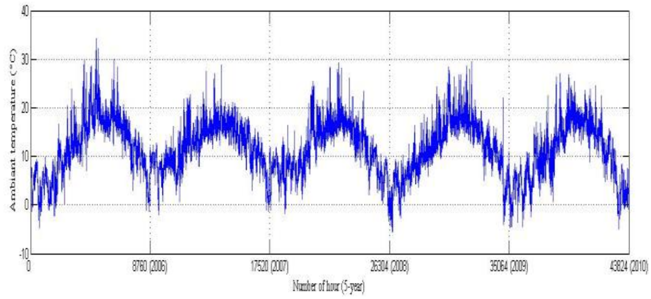

Fig. 7. Average hourly ambient temperature of EREA for a period of 5-year.

Table 1. Technical specifications and the investment costs of PV modules

Model	1	2	3	4
V_{mp} (V)	35.30	35.20	36.80	36.00
I_{mp} (A)	7.65	7.95	8.02	8.34
V_{oc} (V)	44.80	44.80	44.90	45.50
I_{sc} (A)	8.20	8.35	8.53	8.90
$\mu_{V,SC}$ (%/°c)	- 0.37	- 0.34	- 0.34	- 0.335
$\mu_{I,SC}$ (%/°c)	0.06	0.06	0.045	0.047
$NCOT$ (°C)	46.00	45.00	45.00	46.00
A_{PV} (m^2)	1.95	1.94	1.94	1.94
$C_{\_cap,PV}$ (€)	239.58	252.17	213.97	228.65
$C_{\_ins,PV}$ (€)	35.63	38.25	30.87	33.50
$C_{\_O\&M,PV}$ (€/year)	6.64	6.25	6.89	6.85

Table 2. Technical specifications and the investment costs of battery banks.

Model	1	2	3	4
$C_{BAT,nom}$ (Ah)	120.00	150.00	140.00	180.00
$V_{BAT,nom}$ (V)	12.00	12.00	12.00	12.00
DOD (%)	80.00	80.00	80.00	80.00
Efficiency (%)	85.00	85.00	85.00	85.00
$C_{\_cap,BAT}$ (€)	125.34	131.52	137.42	147.90
$C_{\_ins,BAT}$ (€)	17.69	18.56	19.40	20.88
$C_{\_O\&M,BAT}$ (€/year)	4.42	4.89	5.23	5.68

The capital costs' share of the system total investment costs is, on average, around 85 per cent, while the installation costs account for around 12 per cent and the annualized operation and maintenance costs for around 3 per cent. Table 3 shows that the installation cost of wind turbine is also as important as the capital cost in its system total investment cost. The diesel power generator set, as emergency power-supply, which consists of 10 diesel generator units of 40 kW each, is connected to the hybrid power system. The specifications and the investment costs of the diesel generator are shown in Table 4. Additionally, the photovoltaic modules are assumed to be installed, facing south with tilt angle equal to the latitude of the EREA, on the rooftop of the residential buildings. The average surface area of the residential buildings' rooftop is equal to 91 m^2.

Table 3. Technical specifications and the investment costs of wind turbines.

Model	1	2	3	4
P_r (kW)	20	25	30	35
V_{ci} (m/s)	2.00	3.00	3.00	3.50
V_r (m/s)	11.62	11.70	12.00	9.00
V_{oc} (m/s)	25.00	25.00	25.00	25.00
D_{WT} (m)	10.00	12.00	12.56	19.20
$C_{\_cap,WT}$ (€)	860.46	812.93	880.75	932.33
$C_{\_ins,WT}$ (€)	612.93	625.68	672.14	661.10
$C_{\_O\&M,WT}$ (€/year)	40.61	40.86	41.13	53.80
$C_{\_cap,T}$ (€/m)	2.65	2.49	2.55	2.35
$C_{\_ins,T}$ (€/m)	0.89	0.76	0.65	0.81
$C_{\_O\&M,T}$ (€/year)	6.25	6.47	7.15	7.85

Table 4. Technical specifications and the investment costs of diesel generator.

Model	Cummins B3.3
$P_{D,rated}$ (kW)	40
$Pr_{\_fuel}$ (€/l)	1.44
A (l/kWh)	0.2461
B (l/kWh)	0.08415
$C_{\_ins,D}$ (€)	7954
$C_{\_ins,D}$ (€/h)	2.25
$C_{\_aqu,D}$ (€)	533

5.2. Optimum System Configurations and System Total Investment Costs

The optimum system configurations of the hybrid PV/wind/diesel power system with battery banks and the hybrid PV/wind/diesel power system without battery banks which meet the system reliability requirement with the minimum System Initial Equipment Cost (SIEC) and the minimum System Total Investment Cost (STIC) are summarized in Tables 5-6, respectively, including the PV module number, the wind turbine number, the battery bank number, the PV module surface area, the wind turbine installation height, the number of operational hours of diesel generator, the SIEC for the 1st year and their corresponding STIC for 20-year system lifetime.

The curves of the system total investment cost for each optimum configuration versus the number of function evaluations are plotted in Figs. 8-9. The obtained optimum configurations of the hybrid power systems have respectively 14 million euros and 19 million euros system total investment cost for 20-year system lifetime. The minimum values of each system total investment cost are obtained after 22365 and 6559 function evaluations.

Table 5. Optimal configuration,SIEC and STIC of hybrid PV/wind/battery/diesel power system.

Model	1	2	3	4
N_{PV}	903	967	1143	756
N_{WT}	20	17	17	13
N_{BAT}	3713	3579	3846	3299
S_{PV} (m^2)	1761	1876	2218	1460
H_{WT} (m)	17	25	33	41
$N_{d,hour}$ (h)			4953	
SIEC for 1st year (M€)			3.39	
STIC for 20-year (M€)			14	

Table 6. Optimal configuration, SIEC and STIC of hybrid PV/wind/diesel power system.

Model	1	2	3	4
N_{PV}	1759	1733	1719	1767
N_{WT}	493	456	576	559
S_{PV} (m^2)	3430	3362	3335	3428
H_{WT} (m)	15.00	23.00	35.00	39.00
$N_{d,hour}$ (h)			127690	
SIEC for 1st year (M€)			5.91	
STIC for 20-year (M€)			19	

5.3. Detailed Cost Analysis

The system initial equipment cost structure and the system total investment cost structure of the hybrid PV/wind/battery/diesel power system, ranked by the number of year for a period of 20-year, are presented in Tables 7, which consist of the capital cost, the installation cost, the annualized O&M cost, the replacement cost of PV modules, wind turbines and battery banks and the operation cost of diesel generators.

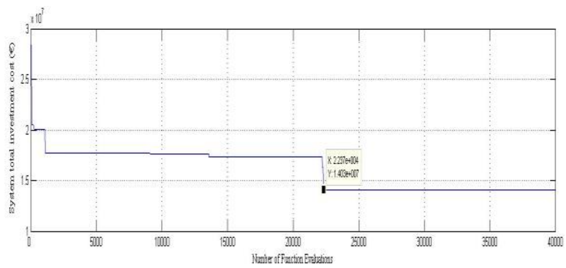

Fig. 8. System total investment cost of hybrid PV/wind/battery/diesel power system.

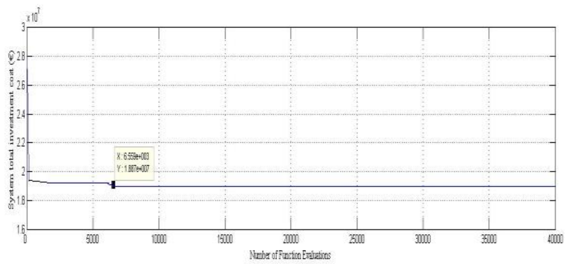

Fig. 9. System total investment cost of hybrid PV/wind/diesel power system.

It can be noticed from the cost structure of hybrid PV/wind/batttery/diesel power system that the System Initial Equipment Cost (SIEC) including the capital cost, the installation cost and the annualized O&M cost of the PV modules and the wind turbines, the capital cost and the installation cost of the battery banks and the annualized operation cost of the diesel generators was found to be the highest of the system total investment cost. The annual system total investment costs which consist of the annualized O&M cost of the PV modules and the wind turbines, the replacement cost of the battery banks and annualized operation cost of the diesel generators were found higher in the years in which the battery banks needed to be replaced. The annual system total investment costs which include the annualized O&M cost of the PV modules, the wind turbines and the battery banks and the annualized operation cost of diesel generators were found to be lower in other years.

However, it should be observed that Tables 7 are based on the data of the Experimental Remote Ecological Area (EREA), so the results might not be entirely representative for the other areas.

Table 7. System total investment cost structure of hybrid PV/Wind/Battery/Diesel power system for 20-year.

Numberof year	Capital cost (M€)			Installation cost (M€)			Annualized O&M cost (M€)			Replacement cost (M€)			DG Cost (M€)	Annual *STIC* (M€)
	PV	WT	BAT	PV	WT	BAT	PV	WT	BAT	PV	WT	BAT		
1 (*SIEC*)	0.88	0.06	1.95	0.13	0.04	0.28	0.03	0.003	0.00	0.00	0.00	0.00	0.021	3.394
2	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.022	0.125
3	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.020	0.123
4	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
5	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.00	0.00	0.00	2.15	0.020	2.203
6	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
7	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.020	0.123
8	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.020	0.123
9	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.00	0.00	0.00	2.15	0.020	2.203
10	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.020	0.123
11	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
12	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
13	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.00	0.00	0.00	2.15	0.020	2.203
14	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.020	0.123
15	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
16	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
17	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.00	0.00	0.00	2.15	0.020	2.203
18	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
19	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
20	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.003	0.07	0.00	0.00	0.00	0.021	0.124
20-year	Total capital cost (M€)			Total installation cost (M€)			Total O&M cost (M€)			Total replacement cost (M€)			Total DG cost (M€)	Total *STIC* (M€)
20-year	2.89			0.45			1.66			8.60			0.41	14

5.4. Impact of Optimum System Configuration on System Performance

According to the result analysis presented and shown in Tables 5-7 and Figs. 8-9, respectively, the impact of the four optimum system configurations on the system performance can be assessed as follows:

1) The system total investment cost of hybrid PV/wind/battery/diesel power system is lower in comparison with the hybrid PV/wind/diesel power system because of the good complementary effect between the solar energy and the wind energy. The different models of system components with their optimum values are combined to match the electrical power demand of the load, ensuring that the system total investment cost is minimized. Also, the number of the operational hours of diesel generators attains its lowest value in this system configuration.
2) The system total investment cost of hybrid PV/wind/diesel power system is more expensive as compared to the hybrid PV/wind/battery/diesel power system because of the increased number of PV modules and wind turbines as well as the operational hours of diesel. The increase of the system components is obviously due to the absence of the storage system. The excess power generated by the PV modules and wind turbines has to be dumped, and once the power is deficit, the diesel generators are operated to supply to electrical power demand of the load. This hybrid power system indicates that the association of battery storage system is necessary to meet the load demand with a lower cost per kWh.

3) It can be noticed from these results that the number of the operational hours of diesel generators is lower in the hybrid power systems including battery storage system which reduce the emission of CO2 in the atmosphere. Contrarily, the operation time of diesel generators increases in the hybrid power system without battery storage system.

6. Conclusion

An optimum sizing study of stand-alone hybrid power system incorporating a combination of several renewable energy sources and alternative energy source with a storage system was presented in this paper. The renewable energy sources were based on the solar PV and wind energy and a set of diesel generators was taken as a traditional alternative power source. A deterministic optimization approach was developed to attain the optimum configuration of each hybrid power system by minimizing the system total investment cost subject to the system component constraints. This study allowed for the achievement of several objectives such as the investigation of the best design layout, sizing optimization of hybrid system components, finding of the lowest system total investment cost and analysis of the system total investment cost details.

The presented study was based on hourly data recorded for 5-year period which is used to assess the technical-economic viability of autonomous hybrid power systems for 20 years system lifetime. These relatively long-term data is very useful to enhance the performance and the reliability of the hybrid power systems.

The hybrid PV/wind/battery/diesel power system and the hybrid PV/wind/diesel power system were studied and optimized in this paper. The results achieved show that the hybrid PV/wind/battery/diesel power system can be considered as the optimum combination system; and most cost-effective to meet the electrical power demand was the best selection in the area of the studies site (EREA). A detailed analysis of the different types of cost (capital cost, installation cost, annualized operation and maintenance cost, replacement cost) for each component of the hybrid PV/wind/battery/diesel power system was presented for the 20 years system lifetime.

The obtained optimum hybrid power system is valid for any location which has a similar meteorological data as the EREA site.

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