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ScienceDirect
Solar Energy 85 (2011) 100–110
SOLAR ENERGY
www.elsevier.com/locate/solener

Optimal sizing study of hybrid wind/PV/diesel power generation unit

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Received 15 July 2010; received in revised form 3 October 2010; accepted 26 October 2010
Available online 18 November 2010

Communicated by: Associate Editor Mukund Patel

Abstract

In this paper, a methodology of sizing optimization of a stand-alone hybrid wind/PV/diesel energy system is presented. This approach makes use of a deterministic algorithm to suggest, among a list of commercially available system devices, the optimal number and type of units ensuring that the total cost of the system is minimized while guaranteeing the availability of the energy. The collection of 6 months of data of wind speed, solar radiation and ambient temperature recorded for every hour of the day were used. The mathematical modeling of the main elements of the hybrid wind/PV/diesel system is exposed showing the more relevant sizing variables. A deterministic algorithm is used to minimize the total cost of the system while guaranteeing the satisfaction of the load demand. A comparison between the total cost of the hybrid wind/PV/diesel energy system with batteries and the hybrid wind/PV/diesel energy system without batteries is presented.

The reached results demonstrate the practical utility of the used sizing methodology and show the influence of the battery storage on the total cost of the hybrid system.

Keywords: Renewable energy system; Power supply; Energy storage; Modeling; Optimization

1. Introduction

For several years, a growing interest in renewable energy resources has been observed. In particular, solar and wind energy are non-depletable, site-dependent, non-polluting, and constitute potential sources of alternative energy options (Elhadisy and Shaadid, 2000). For remote systems such as radio telecommunications, satellite earth stations, or at sites that are far away from a conventional power system, the hybrid energy systems have been considered as preferable (Belfkira et al., 2008a). Such systems are usually equipped with diesel generators to meet the peak load demand during short periods, when there is a deficit of available energy (Borowy and Salameh, 1996).

Hybrid energy systems are best suited to reduce dependence on fossil fuel using available wind speed and solar radiations. A configuration of a hybrid energy system is shown in Fig. 1. It includes PV panels and/or wind turbines and/or diesel generator and/or batteries. These energy systems are considered as one of the cost effective solutions to meet energy requirements of remote areas (Deshmukh and Deshmukh, 2008).

Several authors have studied the hybrid energy systems. McGowan and Manwell (1999) describe the latest advances in wind/PV/diesel hybrid systems with batteries, using data from hybrid systems in various locations in the world. Dufo-Lopez and Bernal-Agustin (2005) have developed the Hybrid Optimization by Genetic Algorithms (HOGA) program helping to determine the optimal configuration of the hybrid PV/diesel system which is precisely described

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doi:10.1016/j.solener.2010.10.018

Nomenclature

A, B	fuel curve coefficients
C_B	nominal capacity of one battery (Ah)
C_D	diesel generator acquisition cost (€)
C_{fuel}	cost of the fuel consumed by the diesel generator (€)
C_I	installation cost function
$C_{I,D}$	installation cost of the diesel generator (€)
C_M	maintenance cost function
C_n	nominal capacity of the battery bank (Ah)
C_T	total capital cost function
C_T,D	total cost of the diesel generator (€)
C^k_{BAT}	capital cost of the battery of type k (€)
C^j_h	wind turbine tower capital cost (€)
C^j_{hm}	wind turbine tower maintenance cost per year (€/year)
$C^k_{i,BAT}$	installation cost of the battery of type k (€)
$C^j_{I,h}$	wind turbine tower installation cost (€)
$C^i_{I,PV}$	capital cost of the PV panel of type i (€)
C^i_{PV}	installation cost of the PV panel of type i (€)
$C^j_{I,WT}$	installation cost of the wind turbine of type j (€)
C^j_{WT}	capital cost of the wind turbine of type j (€)
DOD	depth of discharge of battery bank (Ah)
G_{ref}	irradiance at reference operating conditions equal to 1000 W/m^2
G_T	hourly irradiance on a tilted surface (W/m^2)
I_{max}	maximum current of PV panel at the reference operating conditions (A)
I_{mpp}	PV panel current at the maximum power point (A)
I_{SC}	short circuit current of PV panel (A)
$Life_D$	diesel generator lifetime (h)
M^k_{BAT}	maintenance cost per year of the battery of type k (€/year)
M_D	diesel generator's hourly maintenance cost (€/h)
M^i_{PV}	maintenance cost per year of the PV panel of type i (€/year)
M^j_{WT}	maintenance cost per year of the wind turbine of type j (€/year)
N_{BAT}	total number of the batteries
n_{BAT}	total number of battery units types
$N_{BAT,p}$	number of parallel batteries strings
$N_{BAT,pmax}$	maximum number of parallel batteries strings
$N_{BAT,s}$	number of batteries connected in series
n_{PV}	total number of PV panel types
$N_{PV,p}$	number of parallel PV strings
$N_{PV,s}$	number of PV panels connected in series
N_{WT}	total number of the wind turbines
n_{WT}	total number of wind turbine types
N^k_{BAT}	total number of the batteries of type k
$N^k_{BAT,p}$	total number of parallel battery strings of type k
N^i_{PV}	total number of the PV panels of type i
$N^i_{PV,p}$	total number of parallel PV strings of type i
$N^i_{PV,pmax}$	maximum total number of parallel PV strings of type i
N^j_{WT}	total number of the wind turbines of type j
N^j_{WTmax}	maximum total number of the wind turbines of type j
$NOCT$	normal operating cell temperature (C)
P_D	diesel generator output power (W)
P_B	input/output power of the battery bank (W)
P_L	input power of the DC/AC converter (W)
P_{load}	power demanded by the load (W)
P_{mpp}	PV panel power at the maximum power point (W)
P_R	rated power of the wind turbine (W)
P_{RD}	diesel generator rated power (W)
Pr_{fuel}	fuel price (€/l)
P_{RE}	total power produced by the renewable resources (the PV panels and the wind turbine(s)) (W)
P_{WT}	output power of the wind turbine (W)
SOC	state of charge of the battery bank (Ah)
SOC_{max}	maximum state of charge of the battery bank (Ah)
SOC_{min}	minimum state of charge of the battery bank (Ah)
STC	system total cost (€)
T_a	ambient temperature of the site under consideration (C)
T_c	PV panel operating temperature (C)
$T_{c,ref}$	PV panel temperature at reference operating conditions is equal to 25 °C
$V_{Bat,nom}$	nominal voltage of one battery (V)
V_{Bus}	DC bus voltage (V)
V_{max}	maximum voltage of PV panel at the reference operating conditions (V)
V_{mpp}	PV panel voltage at the maximum power point (V)
V_{OC}	open circuit voltage of PV panel (V)
$V_{PV,nom}$	nominal PV panel voltage (V)
v	wind speed at projected height h (m/s)
v_{ci}	cut-in wind speed of the wind turbine (m/s)
v_{co}	cut-out wind speed of the wind turbine (m/s)
v_{hr}	wind speed at reference height h_r (m/s)
v_r	rated wind speed of the wind turbine (m/s)
η_B	efficiency of the batteries
η_i	DC/AC converter efficiency
γ	power-law exponent (~1/7 for open land)
y^k_{BAT}	expected number of battery replacements
$\mu_{I,sc}$	temperature coefficient for short circuit current (A/°C)
$\mu_{V,oc}$	temperature coefficient for open circuit voltage (V/°C)
Δt	hourly time step

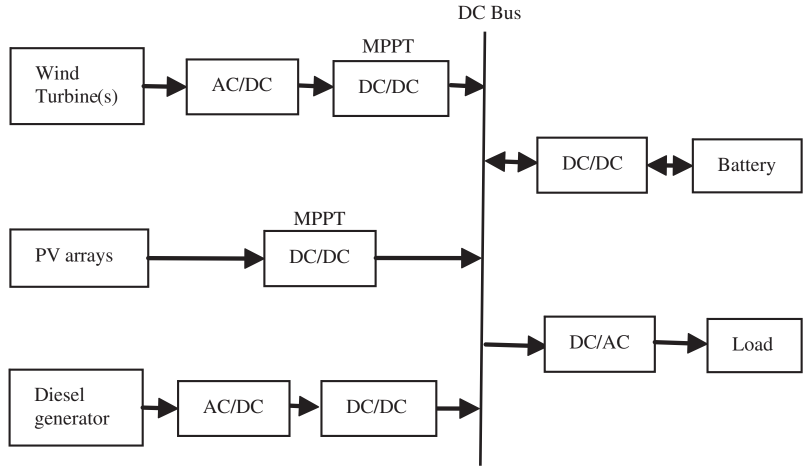

Fig. 1. Block diagram of a hybrid wind/PV/diesel system.

(number and type of PV panels, number and type of batteries, inverter power, diesel generator power and number of running hours per year, optimal control strategy, the system total net present value i.e. cost of the investments plus the discounted present values of all future costs). In Kellog et al. (1998), the generation capacity is determined to best match the power demand by minimizing the difference between generation and load over a 24-h period. In fact, calculation was made on the basis of available hourly average data of wind speed, solar radiations and power demand. The iterative procedure is adopted for selecting the wind turbine size and the number of PV panels needed for a wind/PV stand-alone system to meet a specific load. Celik (2002) presented a techno-economic analysis based on solar and wind biased months for an autonomous hybrid PV/wind energy system. He has observed that an optimum combination of the hybrid PV/wind energy system provides higher system performances than either of the single systems for the same system cost for a given battery storage capacity. Celik has also observed that the magnitude of the battery storage capacity has an important bearing on the system performances of single photovoltaic and wind systems.

Bhuiyan and Asgar (2003) have optimized a PV/battery system for Dhaka in Bangladesh to reach optimum performances for different tilt and azimuth angle with respect to the power output. Koutroulis et al. (2006) have proposed an alternative methodology for the optimal sizing of wind/PV systems. The decision variables included in the optimization process are the number and type of PV panels, wind turbines and battery chargers, the PV panels tilt angle, the installation height of the wind turbines and the battery type and his nominal capacity. The minimization of the cost (objective) function is implemented employing a genetic algorithm approach.

Thus far, the optimal sizing of stand-alone systems developed by most authors is based on a static evaluation of the available energy. More clearly, the power produced by the wind turbines as well as the power produced by PV panels are considered as constant values corresponding to a short term reference. In this paper, the proposed optimization procedure is based on a dynamic evaluation of the wind and solar energetic potential corresponding to a long term reference. This dynamic evaluation of the energetic potential of the site permits the introduction of new constraints making the optimization procedure more flexible like the maximum acceptable time of energy unavailability and the minimum power level authorized regarding the power demand. Consequently, this approach results in a more realistic optimization of the size of hybrid wind/PV/diesel power generation system. The mathematical model of the studied hybrid system and the dynamic optimization approach are described in the following sections. The results and conclusions obtained after applying the sizing optimization methodology for a wind/PV/diesel system with batteries and a wind/PV/diesel system without batteries are shown, verifying the practical utility of the proposed methodology and the economic aspect of the use of batteries.

2. Mathematical model of hybrid system

The models developed in this paper are intended for the sizing of the hybrid system on temporal horizons superior to 6 months. The available data for the wind, the irradiation and the ambient temperature are sampled every hour. Consequently, the mathematical models governing the behavior of each source are chosen to be suitable for the sample duration (1 h) of the site data. So, these models do not take into account the dynamic aspects of the converters behavior. Also, these converters are supposed to be perfectly controlled in order to extract the available maximum power. The presented models in the following subsections are then focused on the ability to simulate the main power transfers between the different components of the studied hybrid system.

2.1. Model of PV panel

The hourly output power of a PV panel can be calculated by several analytical models which define the current–voltage relationships based on the electrical characteristics of the PV panel.

The model presented by Belfkira (2009) allows calculating the PV panel current (I_{mpp}) and voltage (V_{mpp}) at the maximum power point using a maximum power point tracker (MPPT). This model includes the effects of irradiation level and panel temperature on the output power as follows

$$I_{mpp} = I_{SC} \cdot \left\{1 - C_1 \cdot \left[\exp\left(\frac{V_{max}}{C_2 \cdot V_{OC}}\right) - 1\right]\right\} + \Delta I \tag{1}$$

$$V_{mpp} = V_{max} + \mu_{V,OC} \cdot \Delta T \tag{2}$$

and the PV panel power at the maximum power point, P_{mpp}, is expressed as:

$$P_{mpp} = V_{mpp} \cdot I_{mpp} \tag{3}$$

with

$$C_1 = \left(1 - \frac{I_{max}}{I_{SC}}\right) \cdot \exp\left(-\frac{V_{max}}{C_2 \cdot V_{OC}}\right) \tag{4}$$

$$C_2 = \left(\frac{V_{max}}{V_{OC}} - 1\right) \cdot \left[\ln\left(1 - \frac{I_{max}}{I_{SC}}\right)\right]^{-1} \tag{5}$$

$$\Delta I = I_{SC} \cdot \left(\frac{G_T}{G_{ref}} - 1\right) + \mu_{I,SC} \cdot \Delta T \tag{6}$$

$$\Delta T = T_c - T_{c,ref} \tag{7}$$

T_c can be expressed as follows (Markvar, 2000)

$$T_c = T_a + \frac{NOCT - 20}{800} \cdot G_T \tag{8}$$

where normal operating cell temperature ($NOCT$) is defined as the cell temperature when the PV panel operates under 800 W/m^2 of solar irradiation and 20 °C of ambient temperature. $NOCT$ is usually between 42 °C and 46 °C.

Most local observatories provide only solar irradiation data on a horizontal plane (Yang et al., 2007). Thus, an estimate of the solar irradiation incident on any sloping surfaces, as analyzed by Bernard (2004), is needed.

The PV panels are connected in series to form strings, where the number of panels to be connected in series $N_{PV,s}$ is determined by the selected DC bus voltage (V_{Bus}) as follows (Seeling-Hochmuth, 1998)

$$N_{PV,s} = \frac{V_{Bus}}{V_{PV,nom}} \tag{9}$$

Then $N_{PV,s}$ is not subject to the optimization, whereas the number of parallel PV strings, $N_{PV,p}$, is the design variable that needs optimization.

2.2. Model of wind turbine

The hourly output power of wind generator is determined by the average hourly wind speed at the hub height and the output characteristic of the wind generator. Then, before calculating the output power of wind generator, the measured data of average hourly wind speed must be converted to the corresponding values at the hub height. Using the wind speed at a reference height h_r(m) from the database, the velocity at a specific hub height (h(m)) for the location is estimated on an hourly basis throughout the specified period through the following expression (Koutroulis et al., 2006; Belfkira et al., 2008a)

$$v = v_{hr} \cdot \left(\frac{h}{h_r}\right)^{\gamma} \tag{10}$$

In function of this wind speed, the model used to calculate the output power, $P_{WT}(t)$ (W), generated by the wind turbine generator is as follows:

$$P_{WT} = \begin{cases} a \cdot v^3 - b \cdot P_R & v_{ci} < v < v_r \\ P_R & v_r < v < v_{co} \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

where $a = \frac{P_R}{v_r^3 - v_{ci}^3}$ and $a = \frac{v_{ci}^3}{v_r^3 - v_{ci}^3}$

Fig. 2 shows typical wind turbine characteristics.

2.3. Model of battery bank

For the charging process and discharging process of the battery bank, the state of charge (SOC) can be calculated from the following equation

$$SOC(t + \Delta t) = SOC(t) + \eta_{bat}((P_B(t))/V_{bus})\Delta t \tag{12}$$

where η_{bat} is equal to the round-trip efficiency in the charging process and is equal to the 100% in the discharging process (Koutroulis et al., 2006), V_{bus} is the DC bus voltage (V) and Δt is the hourly time step is set equal to 1 h.

For longevity of the battery bank, the maximum charging rate (SOC_{max}) is given as the upper limit, it is equal to the total nominal capacity of the battery bank (C_n(Ah)) which is related to the total number of batteries (N_{BAT}), the number of batteries connected in series ($N_{BAT,s}$) and the nominal capacity of each battery (C_B(Ah)), as follows (Borowy and Salameh, 1996)

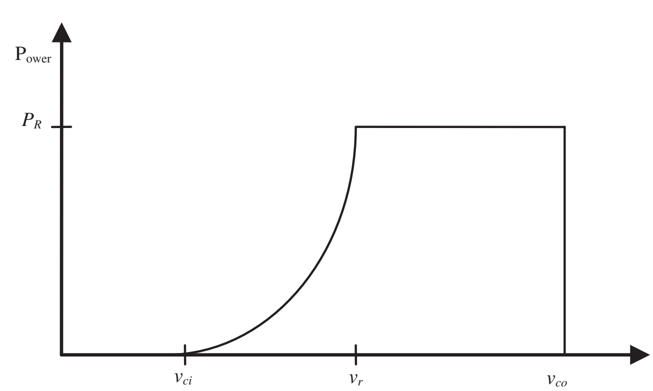

Fig. 2. Wind power versus wind speed.

$$C_n = \frac{N_{BAT}}{N_{BAT},s} \cdot C_B \tag{13}$$

The lower limit that the state of charge of the battery bank cannot exceed at the time of discharging (SOC_{min}) may be expressed as follows

$$SOC_{min} = (1 - DOD) \cdot SOC_{max} \tag{14}$$

The batteries are connected in series to give the desired nominal DC operating voltage and are connected in parallel to yield a desired Ah system storage capacity. Then, the number of batteries connected in series depends on the DC bus voltage and the nominal voltage of each individual battery $V_{bat,nom}$, it is calculated as follows

$$N_{BAT,s} = \frac{V_{bus}}{V_{bus,nom}} \tag{15}$$

The number of batteries to be connected in series is therefore not subject to the optimization but is a straightforward calculation, whereas the number of parallel battery strings, each consisting of $N_{BAT,s}$ batteries connected in series, is a design variable that needs optimization.

2.4. System operation strategies

The power generated by the hybrid system and the amount of energy stored are time dependent. So, the input/output power of the battery bank, is controlled by the following equation (Belfkira et al., 2008b)

$$\Delta P(t) = P_{RE}(t) - P_L(t) \tag{16}$$

where

$$P_L(t) = \frac{P_{load}(t)}{\eta_i} \tag{17}$$

where P_{load} is the power demanded by the load and η_i is the DC/AC converter efficiency specified by the manufacturer.

Depending on the ΔP value, the following cases apply:

(a) If $\Delta P \geqslant 0$: the remaining power will be used to charge the batteries. If the batteries are completely charged, the exceed power is dumped.
(b) If $\Delta P < 0$: the remaining power will be given by the batteries or by the diesel generator, depending on the dispatch strategy:
(i) if the batteries are able to give ΔP, then: batteries discharge and diesel generator turns off

$$P_B(t) = \Delta P(t) \tag{18}$$

(ii) if the batteries are not able to give ΔP, the diesel generator turns on, and the batteries will neither be charged nor discharged. Then the diesel generator output power (PD(W)) is expressed as follows

$$P_D(t) = P_L(t) - P_{RE}(t) \tag{19}$$

(iii) if the diesel generator runs at his rated power P_{RD}, the batteries will be charged with the remaining power

$$P_D(t) = P_{RD} \tag{20}$$

and

$$P_B(t) = (P_{RE}(t) + P_D(t)) - P_L(t) \tag{21}$$

3. Optimal sizing algorithm

3.1. DIRECT algorithm

Many researchers have recently proved that the DIRECT algorithm, acronym for DIviding RECTangles and developed by Jones et al. (1993), is an effective deterministic algorithm to find the global optimum of several problems (Belfkira et al., 2008b)

$$\begin{cases} \min\limits_x f_i(x) & i \in [1, n] \\ h_k(x) = 0 & k \in [1, p] \\ g_j(x) >= 0 & j \in [1, q] \\ x_l \leqslant x \leqslant x_u \end{cases} \tag{22}$$

where $f \in R^n$ are the objective functions and $h_k \in R^p$, $g_j \in R^q$ are respectively the equality and the inequality constraints.

The first step of the DIRECT algorithm is to transform the search space to be the unit hypercube. The function is then sampled at the center-point of this cube. Computing the function value at the center-point instead of doing it at the vertices is an advantage when dealing with problems in higher dimensions. The hypercube is then divided into smaller hyperrectangles whose center-points are also sampled. Instead of using a Lipschitz constant when determining the rectangles to sample next, DIRECT identifies a set of potentially optimal rectangles in each iteration. All potentially optimal rectangles are further divided into smaller rectangles whose center-points are sampled. When no Lipschitz constant is used, there is no natural way of defining convergence. Instead, the procedure described above is performed for a predefined number of iterations. More description can be found in (Belfkira et al., 2008b).

The DIRECT optimal sizing methodology, presented in this paper, outputs the optimum numbers and the types of the components of the hybrid system, ensuring that the system total cost is minimized subject to the constraint that the load energy demand is completely covered.

3.2. Objective function and constraints

The objective function taken here is the system total cost, $STC(x)$ (€), which is equal to the sum of the total capital cost function $C_T(x)$, the maintenance cost function $C_M(x)$, the installation cost function $C_I(x)$ and the total cost of the diesel generator $C_{T,D}$, throughout the life of the system which is assumed equal to the lifetime of the

PV panels which are the elements that have a longer lifetime that is equal to 20 years. The objective function to be minimized is then, expressed as follows

$$\min_x STC(x) = \min_x \{C_T(x) + C_M(x) + C_I(x) + C_{T,D}\} \quad (23)$$

where x is the vector of the sizing variables $x = \{N_{PV,p}, N_{WT}, N_{BAT,p}\}$.

Then, the optimization procedure is achieved by minimizing the system total cost function (Eq. (24)) consisting of the sum of the individual system devices capital, the 20-year round maintenance costs and the installation costs

$$\begin{aligned} STC(N_{PV,p}, N_{WT}, N_{BAT,p}) &= \sum_{i=1}^{n_{PV}} N_{PV}^i.(C_{PV}^i + 20 \cdot M_{PV}^i + C_{I,PV}^i) \\ &+ \sum_{j=1}^{n_{WT}} N_{WT}^J \cdot (C_{WT}^i + 20 \cdot M_{WT}^j + C_{I,WT}^j + C_h^j + 20 \cdot C_{hm}^j + C_{I,h}^j) \\ &+ \sum_{k=1}^{n_{BAT}} N_{BAT}^k \cdot (C_{BAT}^k + C_{I,BAT}^k + y_{BAT}^k(C_{BAT}^k + C_{I,BAT}^k) \\ &+ (20 - y_{BAT}^k - 1) \cdot M_{BAT}^k) + C_{T,D} \end{aligned} \quad (24)$$

y_{BAT}^k is the expected number of battery replacements during the 20-year system operation, because of limited battery lifetime. The costs of converters and other components are included in the installation cost (Belfkira et al., 2008a).

The total cost of the diesel generator ($C_{T,D}$(€)) is calculated as follows

$$C_{T,D} = C_{I,D} + M_D + \frac{C_D}{Life_D} + C_{fuel} \quad (25)$$

where $C_{I,D}$ is the installation cost of the diesel generator (€), M_D is the diesel generator's hourly maintenance cost (€/h), C_D is the diesel generator acquisition cost (€), $Life_D$ is the diesel generator lifetime (h) and C_{fuel} is the cost of the fuel consumed by the diesel generator (€).

Diesel Generator has typically a maximum fuel efficiency of about 3 kW h/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 (Ashari and Nayar, 1999). The following equation shows the fuel consumption cost for 1 h of running of the diesel generator (Skarstein and Ulhen, 1989)

$$C_{fuel} = Pr_{fuel} \cdot (A \cdot P_D + B \cdot P_{RD}) \quad (26)$$

where Pr_{fuel} is the fuel price (€/l), $A = 0.246$ l/kW h and $B = 0.0845$ l/kW h are the fuel curve coefficients.

The minimization of the objective function is subject to the constraints that the power produced by the system is equal to the power demanded by the load and the state of charge of the battery bank is limited between SOC_{min} and SOC_{max} as follows

$$\begin{cases} P_P = P_L \\ SOC_{min} \leqslant SOC \leqslant SOC_{max} \end{cases} \quad (27)$$

where P_P is the power produced by the system, it is calculated as follows

$$P_P = P_{RE} + P_D - P_B \quad (28)$$

where P_{RE} is the power produced by the renewable resources as follows

$$P_{RE} = \sum_{i=1}^{n_{PV}} N_{PV}^i \cdot P_{mpp}^i + \sum_{j=1}^{n_{WT}} N_{WT}^j \cdot P_{WT}^j \quad (29)$$

where P_{mpp}^i and P_{WT}^j are respectively the power at the maximum power point of the PV panel of type i(W) and the output power of the wind turbine of type j(W), n_{PV} and n_{WT} are respectively the total number of PV panel types and wind turbine types and $N_{PV}^i = N_{PV,p}^i \times N_{PV,s}^i$ is the total number of PV panels of type i and N_{WT}^j is the total number of wind turbines of type j.

P_B is the input/output power of the battery bank, $P_B > 0$ during the charging process of the battery and $P_B < 0$ in the discharging process as calculated in the Eqs. (18) and (21).

Additional constraints to be imposed are

$$\begin{aligned} &1 \leqslant N_{PV,p}^i \leqslant N_{PV,pmax}^i \\ &1 \leqslant N_{WT}^j \leqslant N_{WTmax}^j \\ &1 \leqslant N_{BAT,p}^k \leqslant N_{BAT,pmax}^k \end{aligned} \quad (30)$$

where $N_{PV,pmax}^i$, $N_{WT,pmax}^j$ and $N_{BAT,pmax}^k$ were calculated according to the nominal power of PV panel, wind turbine and nominal capacity of battery, respectively, and the peak of the load demand.

Then, the model of the sizing optimization of the stand-alone hybrid wind/PV/diesel system is expressed as follows

$$\begin{cases} \min_x STC(x) = \min_x \{C_A(x) + C_M(x) + C_I(x) + C_{T,D}\} \\ \quad \text{where } x = \{N_{PV,p}^i, N_{WT}^j, N_{BAT,p}^k\} \\ P_P(t) = P_L(t) \\ SOC(t) \geqslant SOC_{min} \\ SOC(t) \leqslant SOC_{max} \\ 0 \leqslant N_{PV,p}^i \leqslant N_{PV,pmax}^i \\ 0 \leqslant N_{WT}^j \leqslant N_{WTmax}^j \\ 0 \leqslant N_{BAT,p}^k \leqslant N_{BAT,pmax}^k \end{cases} \quad (31)$$

4. Dakar's site hybrid system sizing results

The developed methodology has been applied to design the stand-alone hybrid wind/PV/diesel system in order to power supply a varying load of 15 kW as peak, located in the area of Dakar in Senegal with geographical coordinates defined as: latitude: 14°41N, longitude: 17°27W and altitude: 24 m above sea level.

The collection of 6 months of data of wind speed, solar radiation and ambient temperature recorded for every hour, during the period of 1st January–30 June 2003, were used and are plotted in Fig. 3. The wind speed was measured at a 20 m height which is considered as the reference height for the site indicated above (cf. Eq. (10)). The hourly

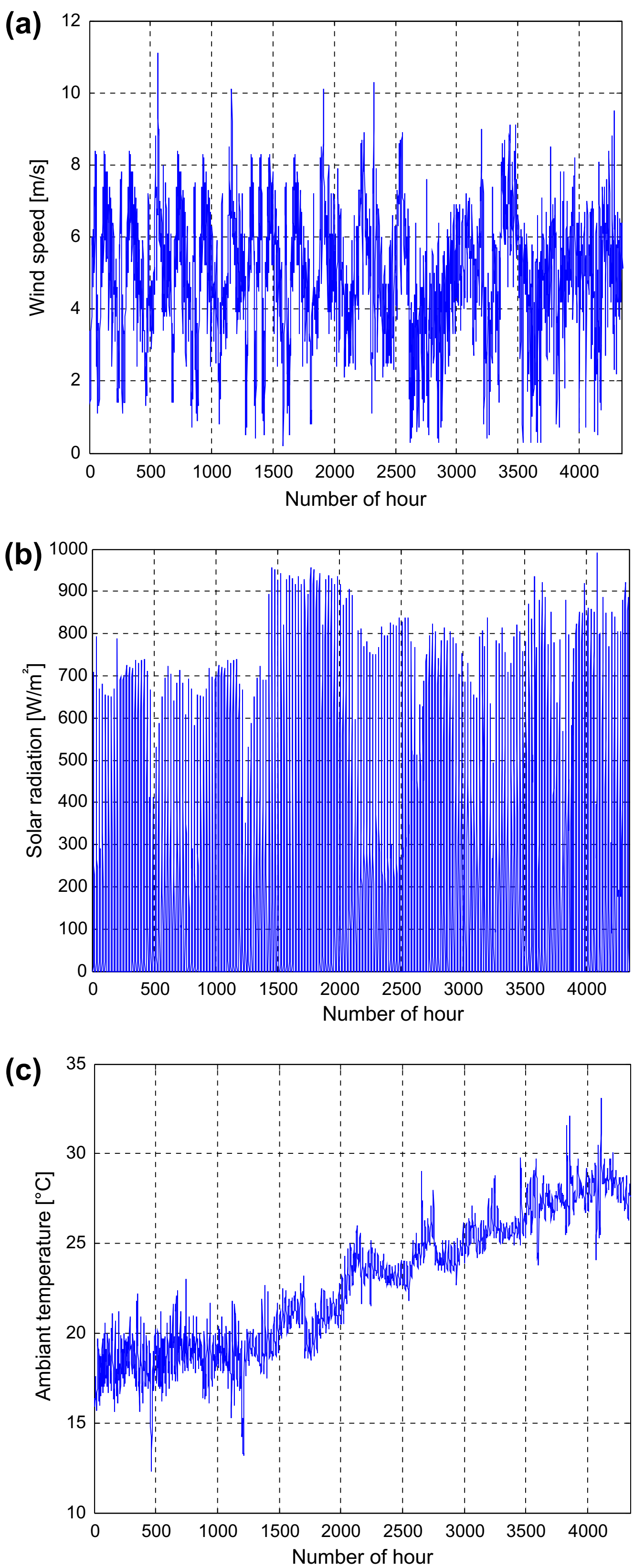

Fig. 3. Hourly mean values during a period of 6 months of meteorological conditions: (a) wind speed, (b) solar radiation and (c) ambient temperature.

distribution of the consumer power requirements during a day is shown in Fig. 4.

In this application, one diesel generator of a rated power of 16 kW (standard rated power of a diesel generator) and four types of wind turbines, PV panels and batteries have been used. The specifications and the related capital as well as maintenance and installation costs of each component type are listed in Tables 1–3. These elements constitute the inputs of the optimal sizing procedure. The maintenance cost of each unit per year and the installation cost of each component have been set at 1% and 10% respectively of the corresponding capital cost. The PV panel lifetime is 20 years. The diesel generator lifetime is 7000 h. The fuel price is 0.9 €/l. The capital cost and the maintenance cost of the diesel generator are respectively 6830 € and 0.2 €/h.

The DC bus voltage is chosen to be equal to 48 V. Hence, the PV panels and batteries numbers connected in series are determined to fulfill the DC bus voltage. The expected battery lifetime has been set to 3 years with proper maintenance, resulting in $y_{BAT}^{k} = 6$. Since the tower heights of wind turbines affect the results significantly, 36 m high tower is chosen.

The minimization of the system total cost is achieved by selecting an appropriate system configuration.

The optimal sizing results of the two hybrid systems (e.g. wind/PV/diesel system with battery bank and wind/PV/diesel system without battery bank) are presented in Tables 4 and 5 respectively where the different types of devices, their numbers and the related total costs are listed.

The obtained optimal configurations of the hybrid system with battery bank and the hybrid system without battery bank have respectively 388.540 k€ and 2.9775×10^3 k€ total costs for 20-year operation. The variations of these costs during the optimization procedure are presented in Figs. 5 and 6, respectively. In order to guarantee the convergence of the minimization algorithm, the maximum number of the function evaluations is chosen equal to 8000. The minimum values of the total costs of the hybrid system with battery bank and the hybrid system without

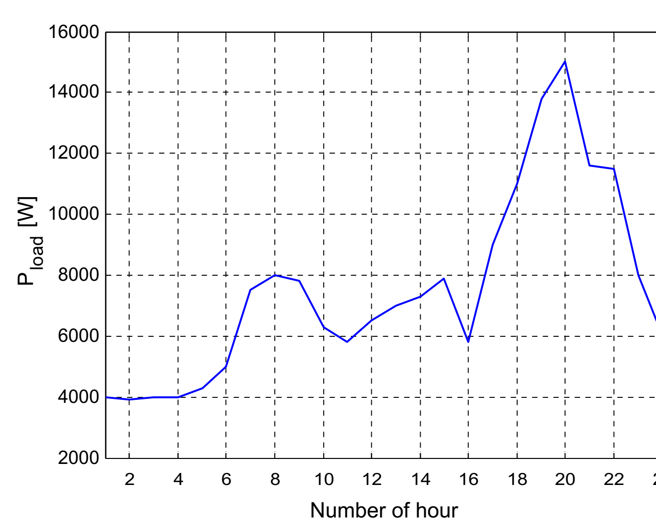

Fig. 4. Hourly demanded power in a day.

Table 1
Photovoltaic panels specifications.

Type	1	2	3	4
V_{oc} (V)	33.2	33.2	36.6	36.8
I_{sc} (A)	8.85	8.78	8.09	8.34
V_{max} (V)	26.6	26.6	29.3	29.8
I_{max} (A)	7.9	8.09	7.52	7.71
$NCOT$ (°C)	47.9	47.9	45	45
Capital cost (€)	331.59	442.31	447.56	467.8
Installation cost (€)	33.2	44.2	44.8	46.8
Maintenance cost per year (€/year)	3.32	4.42	4.48	4.68

Table 2
Wind turbines specifications.

Type	1	2	3	4
Power rating (kW)	5	10	20	50
v_r (m/s)	10	10	11	11
v_{ci} (m/s)	2	2	2	2
v_{co} (m/s)	18	18	18	18
Capital cost (€)	11,086	16,578	31,958	96,600
Installation cost (€)	1108.6	1657.8	3195.8	9659.9
Maintenance cost per year (€/year)	110.86	165.78	319.58	965.99
Tower capital cost (€)	741	741	741	741
Tower installation cost (€)	74.1	74.1	74.1	74.1
Tower maintenance cost per year (€/year)	7.41	7.41	7.41	7.41

Table 3
Batteries specifications.

Type	1	2	3	4
Nominal capacity (Ah)	104	108	212	285
Voltage (V)	12	12	12	12
DOD (%)	80	80	80	80
Efficiency (%)	85	85	85	85
Capital cost (€)	206.40	265.04	493.26	588.23
Installation cost (€)	20.7	26.5	49.3	58.9
Maintenance cost per year (€/year)	2	2.7	5	5.9

Table 4
Optimal configuration and cost of wind/PV/diesel system with battery bank.

Type	1	2	3	4
$N_{PV,p}$	2	9	1	0
N_{WT}	0	0	2	0
$N_{BAT,p}$	5	3	3	2
Cost (k€)	388.540			

Table 5
Optimal configuration and cost of wind/PV/diesel system without battery bank.

Type	1	2	3	4
$N_{PV,p}$	45	9	11	17
N_{WT}	0	0	0	0
Cost (k€)	2.9775×10^3			

battery bank are obtained after 5300 function evaluations and 943 function evaluations respectively. For these results, one can notice that, for the hybrid system without battery bank, a near optimal solution was derived during the early stages of the function evaluations (elimination of batteries constraints).

The number of operating hours of the diesel generator during the period of 20 years is equal to 24,020 h for the hybrid system with battery bank and equal to 66,020 h for the hybrid system without battery bank.

From all these results, one can verify that to supply a variable load of 15 kW as peak installed in the site of Dakar, the use of the battery bank in the hybrid wind/PV/diesel system is determinant for reducing the number of operating hours of the diesel generator reducing by the fact the total cost of the 20 years operating hybrid system.

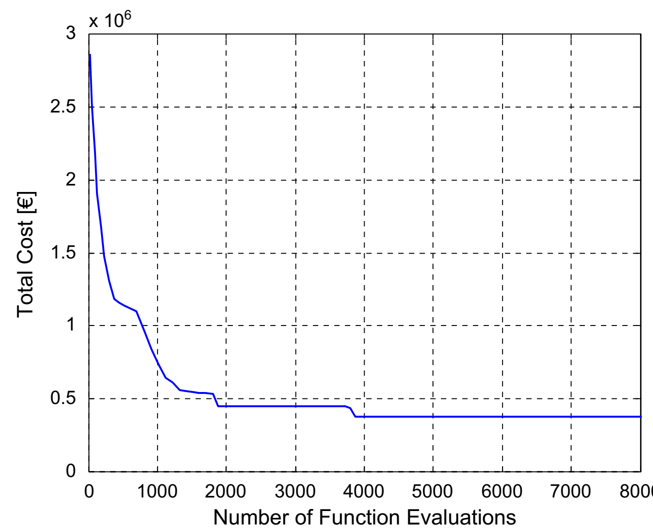

Fig. 5. System total cost during the DIRECT optimization of the hybrid wind/PV/diesel with battery bank.

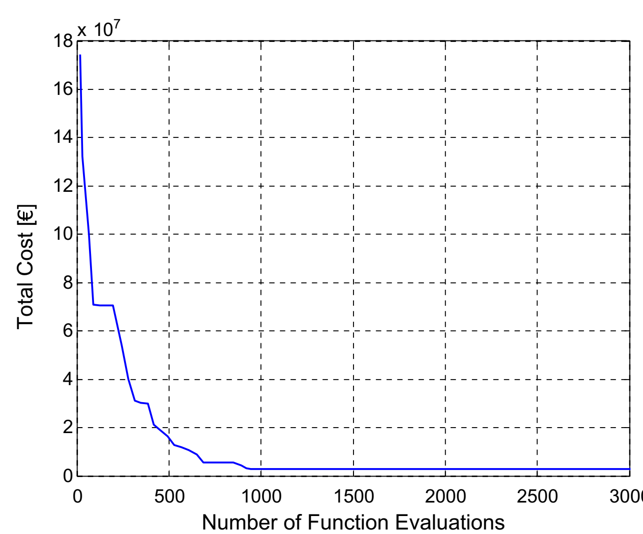

Fig. 6. System total cost during the DIRECT optimization of the hybrid wind/PV/diesel without battery bank.

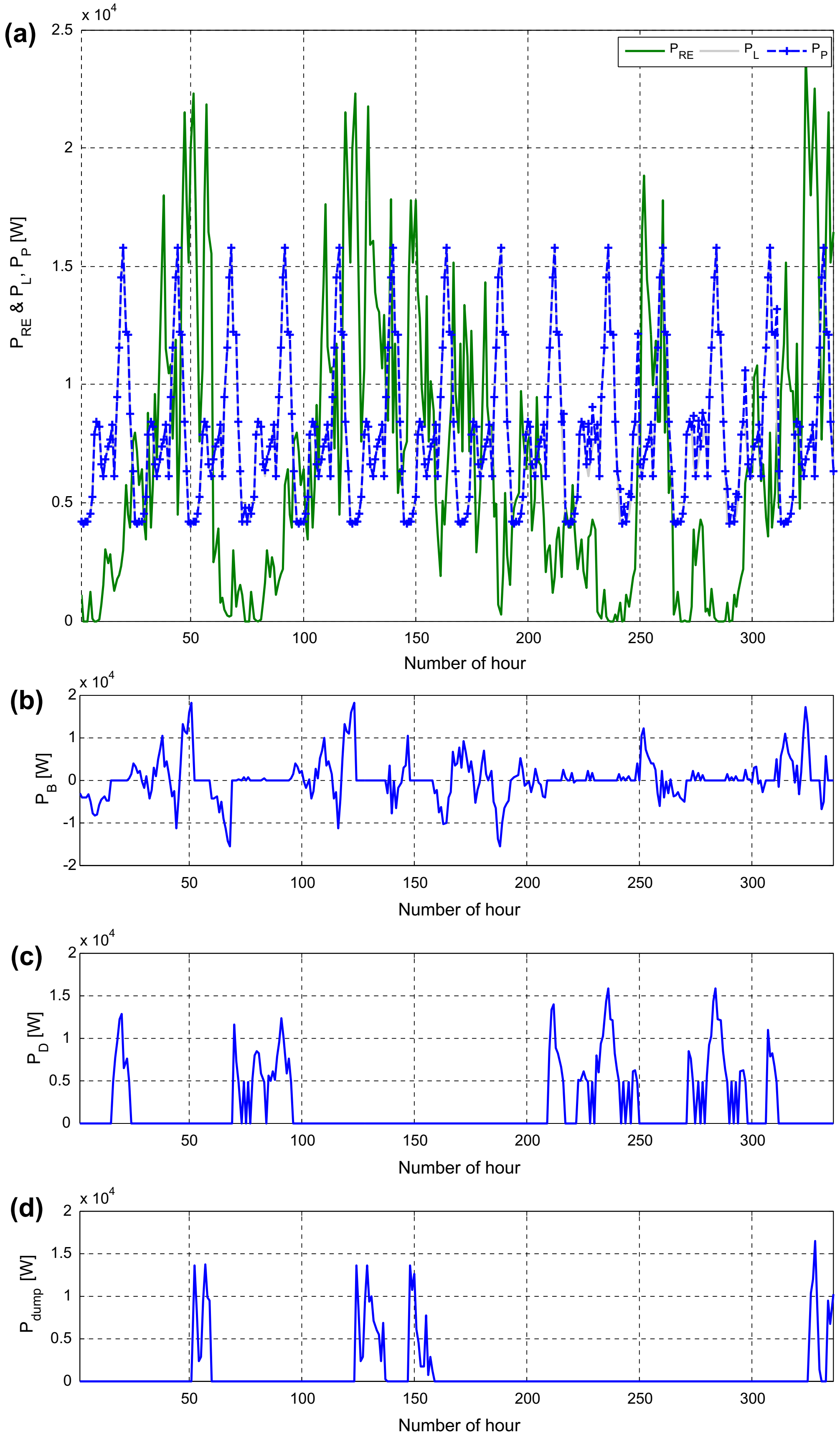

Fig. 7. (a) Renewable sources, demand and system powers, (b) charge and discharge of the battery bank, (c) diesel generator power and (d) dump power.

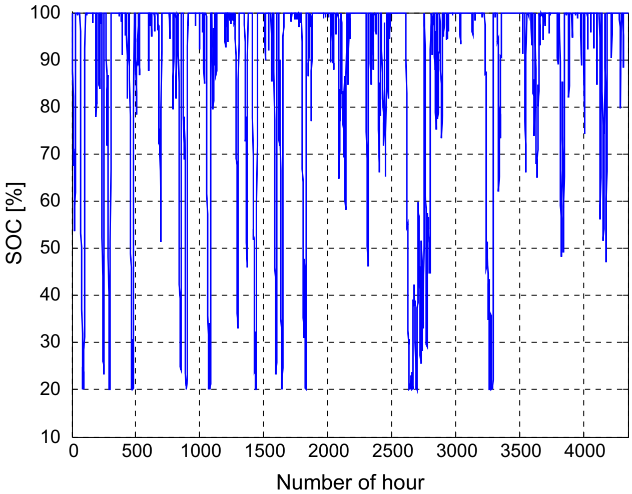

Fig. 8. State of charge of the battery bank.

In order to study the hourly behavior of the obtained optimal configuration of the hybrid wind/PV/diesel system with battery bank (Table 4), the results of a simulation conducted on a period from 1st to 15th January in 2003 are reported in Fig. 7. Thus, the power supply from the renewable sources P_{RE}, the power demanded by the load P_L and the power produced by the hybrid system P_P are shown in Fig. 7a. Also, Fig. 7b shows the input/output battery bank power P_B. Fig. 7c shows the power produced by the diesel generator and Fig. 7d shows the dump power.

According to the first model constraint (Eq. (31)), one can verify in Fig. 7a, that the power produced by the hybrid system (equal to the renewable sources power plus the diesel generator power minus the input/output battery bank power) is equal to the power demanded by the load. Also, from Fig. 7a and b, one can observe that when the renewable sources power is greater than the power demand, the surplus power is stored in the battery bank ($P_B > 0$). Conversely, when the renewable sources power is smaller than the power demand, the insufficient power is supplied by the battery bank ($P_B < 0$) or by the diesel generator as shown in Fig. 7c. Furthermore, from Fig. 7d, one can suggest that when the power produced by the renewable sources is greater than the demanded power and the battery bank is completely charged, the surplus of the energy can be used for the pumping of water or for the other functioning according to the needs of the region where the hybrid system is installed.

Finally, in Fig. 8, one can note that the state of charge of the battery bank can never exceed the permissible maximum value SOC_{max} (100% of SOC), and can never be below the permissible minimum value SOC_{min} (20% of SOC) (cf. Eq. (14)).

5. Conclusion

A methodology of optimal sizing of a stand-alone hybrid wind/PV/diesel system using a deterministic approach (the DIRECT algorithm) is proposed in this paper. First, the used models of the wind turbines, the PV panels and the storage unit composing the hybrid system, were presented. Then, the proposed optimization procedure was exposed and the main ideas of the DIRECT algorithm were explained. Finally, the developed sizing procedure was applied to optimize a hybrid wind/PV/diesel system. The developed methodology is based on the use of long-term data of wind speed, solar radiation and ambient temperature of the site of Dakar (Senegal). The optimization procedure resulted in the determination the optimum numbers and the types of wind turbines, of PV panels and of batteries, ensuring that the system total cost is minimized while guaranteeing the availability of the energy.

Obtained results show clearly the great impact of the site energetic potential (wind and solar radiation) as well as the load profile on the optimal hybrid system constitution (numbers of wind turbines, of PV panels and of batteries) and the related cost of the hybrid system. Also, the use of long-term data of the renewable resources is very helpful to enhance the performances of the optimal solution. Finally, the stand-alone hybrid wind/PV/diesel system with battery bank seems to be a motivating techno-economic solution to meet the energy demand of remote consumers in regions as the Dakar's site where the number of operating hours of the diesel generator has to be reduced.

Acknowledgment

This work was financially supported by the region of "Haute-Normandie", in France.

References

Ashari, M., Nayar, C.V., 1999. An optimum dispatch strategy using set points for a photovoltaic (PV)–diesel-battery hybrid power system. Solar Energy 66 (1), 1–9.

Belfkira, R., 2009. Modélisation et optimisation de centrales multi-sources de production d'énergies électrique: application aux sites isolés. Ph.D. Thesis, University of Le Havre.

Belfkira, R., Barakat, G., Nichita, C., 2008a. Sizing optimization of a stand-alone hybrid power supply unit: wind/PV system with battery storage. International Review of Electrical Engineering (IREE) 3 (5).

Belfkira, R., Nichita, C., Reghem, P., Barakat, G., 2008b. Modeling and Optimal Sizing of Hybrid Renewable Energy System. In: International Power Electronics and Motion Control Conference ~EPE-PEMC 2008~, Poznan, Poland.

Bernard, J., 2004. Energie solaire: calculs et optimisation. Ellipses-Paris, 53–93.

Bhuiyan, M.M.H., Asgar, M.A., 2003. Sizing of a stand-alone photovoltaic power system at Dhaka. Renewable Energy 28 (6).

Borowy, B.S., Salameh, Z.M., 1996. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Transactions on Energy Conversion 11 (2).

Celik, A.N., 2002. Optimization and techno-economic analysis of autonomous photovoltaic–wind-hybrid energy systems in comparison to single photovoltaic and wind systems. Energy Conversion and Management 43 (18).

Deshmukh, M.K., Deshmukh, S.S., 2008. Modeling of hybrid renewable energy systems. Renewable & Sustainable Energy Reviews 12, 235–249.

Dufo-Lopez, R., Bernal-Agustin, J.L., 2005. Design and control strategies of PV–diesel systems using genetic algorithms. Solar Energy 79, 33–46.

Elhadisy, M.A., Shaadid, S.M., 2000. Parametric study of hybrid (wind + solar + diesel) power generating systems. Renewable Energy 21, 129–139.

Jones, D.R., Perttunen, C.C., Stuckman, B.E., 1993. Lipschitzian optimization without the Lipschitz constant. Journal of Optimization Theory and Applications 79, 157–181.

Kellog, W.D., Nehir, M.H., Venkataramanan, G., Gerez, V., 1998. Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems. IEEE Transactions on Energy Conversion 13 (1).

Koutroulis, E., Kolokotsa, D., Potirakis, A., Kalaitzakis, K., 2006. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. Solar Energy 80 (9).

Markvar, T., 2000. Solar Electricity, second ed. J. Wiley & Sons.

McGowan, J.G., Manwell, J.F., 1999. Hybrid wind/PV/diesel systems experiences. Renewable Energy 16, 1–4.

Seeling-Hochmuth, G., 1998. Optimisation of Hybrid Energy Systems Sizing and Operation Control. Dissertation in Candidacy for the Degree of Dr.-Ing, University of Kassel.

Skarstein, O., Ulhen, K., 1989. Design considerations with respect to long-term diesel saving in wind/diesel plants. Wind Engineering 13 (2).

Yang, H., Lu, L., Zhou, W., 2007. A novel optimization sizing model for hybrid solar-wind power generation system. Solar Energy 81, 76–84.