International Journal of the Physical Sciences Vol. 7(18), pp. 2647-2655, 9 May, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS12.272
ISSN 1992 - 1950 © 2012 Academic Journals

Full Length Research Paper

Methodology to Size an Optimal Standalone Hybrid Solar-Wind-Battery System using Genetic Algorithm

Ould Bilal B[1, 2]*, Ndiaye P. A[1], Kébé C.M.F. [1], Sambou V[1] and Ndongo M[2]

[1]Centre International de Formation et de Recherche en Energie Solaire (C.I.F.R.E.S) ESP BP: 5085 Dakar Fann, Sénégal.
[2]Centre de Recherche Appliqué aux Energies Renouvelables, de l'eau et du froid (CRAER)/FST/Université de Nouakchott BP: 5026 Nouakchott, Mauritanie.

Accepted 02 May, 2012

This paper presents a methodology to calculate the optimal size of a stand-alone hybrid Wind-photovoltaic (PV)-Battery system. The study was interested in the influence of the wind and solar potential and the shape of the load profile on the optimal configuration. The collection of one year of wind speed, solar radiation and ambient temperature, recorded every hour in Kayar and Potou located in the northwestern of Senegal were used with the manufacturer's specifications of a wind turbine and a photovoltaic (PV) panel to calculate the power generated by the wind turbine and the PV modules for each hour of the day. The mathematical modeling of the principal elements of the hybrid wind/PV system is presented showing the main sizing variables. The results of simulations, by the use of the load profile n°1, show that the optimal configuration was hybrid system wind/PV/batteries with 71% and 64% of energy coming from the wind turbine on the site of Potou and Kayar, respectively. The results also show that the load profile n°2 was more suited to the hourly wind and solar energy output for the two sites compared to the rest of the load profiles.

Key words: Hybrid system, load profile, modeling, optimization, genetic algorithm, solar energy, wind energy.

INTRODUCTION

Fossil fuels play a key role in meeting the global energy demand. However, fossil fuel reserves are limited and the use of these sources has adverse impacts on the environment. Therefore, it is necessary to resort to renewable energy sources like solar and wind energy (Akdag and Dinler, 2009).

In remote regions, electric energy is usually supplied by diesel generators. In most cases, supplying the energy demand using diesel fuel is expensive and has negative effects on the environment. Thus, the hybrid system (PV-Wind-Battery) can become competitive with the use of diesel generators (Colle and Abreu, 2004). Further, the use of a single renewable energy source such as wind or solar energy is inadequate to meet the demand for long periods due to the high cost of the system including battery storage (Zhou et al., 2010; Boudy et al., 2010a, 2012a).

To meet this challenge, renewable energy sources such as wind and solar energy can be used in combination to create hybrid (PV-Wind-Battery) systems. Furthermore, the problem caused by the natural variation of the wind and the solar resources can be partially solved by integrating them efficiently. The hybrid system that combines solar and wind generating units with battery backup can attenuate their individual fluctuations and reduce energy storage requirements significantly (Boudy et al., 2010a) thereby reduces the overall cost of system.

Some studies (Borowy and Salameh, 1996; Kellogg et al., 1998; Duffo-Lopes et al., 2005; Ekren, 2008) have used a technical method such as graphical construction method, probabilistic approach and iterative technique to size a hybrid system which was, most often, Wind-Battery, Wind-Battery-Generator, PV-Battery or PV-Battery-Generator. These sizing methodologies did not take into account some components of the system such as regulator (PV batteries charger) and inverter, which

*Corresponding author. E-mail :boudy_bilal@yahoo.fr.

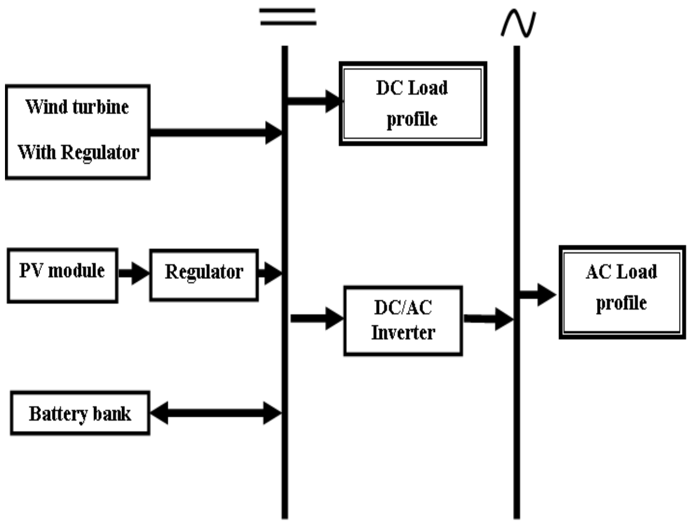

Figure 1. Block diagram of the hybrid PV-Wind-Battery) system.

also greatly affect the acquisition cost of the system.

In this paper, the developed methodology for the calculation of the optimum size of a stand-alone hybrid system was based on the use of the genetic algorithm for sizing the optimal configuration of hybrid system Wind-PV-Battery by minimizing the Annualized Cost of System (ACS). An original approach was to use the decision variables such as PV module size, wind turbine size, battery capacity, number of regulators and inverters in the optimization process. A study on the influence of wind and solar potential variation and the influence of the shape of load profile on the optimal configuration was carried out. The application of this methodology was carried out for the two sites kayar and Potou located in the northwestern coast of Senegal. In this area, there are remote village which are not connected to the national grid. On the other hand, most of gardening activities in the country are concentrated in this region thus, several sites were selected for studies, to produce electricity using wind and solar energy, on the basis that these rural areas constitute major agricultural belts (Boudy, 2005; Youm et al., 2005; Kebe et al., 2008; Boudy et al., 2008, 2007, 2010b, 2011, 2012b; Drame et al., 2012). Furthermore, water pumping for irrigation and rural electrification are identified as one of the viable application of wind and solar energy (Youm et al., 2005).

To achieve the target of this study, technologies of a small wind turbine (EolSenegal/500W), a Battery (Banner C20-963.51/180Ah/12V), a PV module (monocristallin 150Wc/24V), a regulator (REGTARGOM430/ 40A/48V) and an inverter (SINWAVE/3.5 kW/48V) were used.

MODEL OF THE HYBRID SYSTEM COMPONENTS

Figure 1 shows a schematic diagram of a hybrid system (solar-wind-battery). The energy produced by the wind turbines and the PV modules was used to power the load. The remainder is sent to batteries to be stored. If demand exceeds the energy generated by the wind turbines and PV modules, then the battery provides the energy deficit. Figure 1 depicts the various components of the hybrid system (PV-Wind-Battery).

PV array performance model

The photovoltaic module performance is highly affected by the weather, especially the solar irradiation and the PV module temperature. In this paper, a simplified simulation model is used to estimate the PV module performance.

To estimate the PV array output, the solar radiation available on the module surface, the ambient temperature and the manufacture data for the PV module (Table 1) are used as model inputs. The calculation method of the PV array output is given by Equation 4.
The short circuit current and open circuit voltage of a solar photovoltaic module are given by Equations 1 and 2 (Koutroulis et al., 2006):

$$I_{sc} = \left[I_{scst} + K_i \cdot (T_c - 25)\right] \cdot \frac{G}{1000} \quad (1)$$

$$V_{oc} = V_{ocst} - K_v \cdot T_c \quad (2)$$

I_{scst} (A) is the short circuit current standard, K_i (A/°C) is the short circuit current temperature coefficient, G (W/m²) is the global irradiation incident on the PV module, V_{ocst} (V) is the open circuit voltage standard, K_v (V/°C) is the open circuit voltage temperature coefficient and T_c (°C) is the temperature which can be estimated from the ambient temperature T_a (°C) and the solar radiation (Equation 3):

$$T_c(t) = T_a + \left(\frac{NCOT - 20}{800}\right) \cdot G \quad (3)$$

NCOT (°C) is the nominal operating cell temperature.
A photovoltaic module power output at time t is given by Equation 4.

$$P_{pv} = V_{oc} \cdot I_{sc} \cdot FF \quad (4)$$

FF (dimensionless) is the fill factor, dependent on technology of solar modules, which is the ratio between the nominal and the maximum power standard (Koutroulis et al., 2006).

Wind turbine performance model

The average power output from a wind turbine is the power produced at each wind speed multiplied by the fraction of the time that wind speed is experienced, integrated over all possible wind speeds. In integral form, the equation is (Borowy and Salameh, 1994; Boudy et al., 2012a, 2012b):

$$P_{wa} = \int_0^{+\infty} P_w \cdot f(v) \cdot dv \quad (5)$$

Table 1. Specifications of the components.

Components	Specifications
Type of wind Turbine	**Elosenegal/500W/24**
Cut-in speed (m/s)	3
Nominal speed (m/s)	7
Maximum speed (m/s)	10
Nominal power (W)	500
Nominal voltage (V)	24
Cost (Euro)	1 077
Type of module PV	**150W/24V**
Rate voltage (V)	24
Voltage of open circuit (V)	43.4
Current of short-circuit (A)	4.7
Power peak (W)	150
Fill factor	0.74
Cost (Euro)	900
Type of battery	**Banner C20-963.51**
Nominal voltage of battery (V)	12
Nominal capacity (Ah)	180
Cost (Euro)	285
Type of regulator	**REGTARGOM430**
Nominal current (A)	40
Nominal voltage (V)	48
Cost (Euro)	398
Type of inverter	**SINWAVE**
Nominal Power (W)	3 500
Nominal voltage (V)	48
Cost (Euro)	2799

f(v) is a probability density function given by Equation 6, P_w, is the electrical power output of the wind turbine defined by Equation 7 (Justus, 1978; Boudy et al., 2011, 2012b).

$$f(v)=\frac{k}{A}\cdot\left(\frac{v}{A}\right)^{k-1}\cdot\exp\left[-\left(\frac{v}{A}\right)^{k}\right] \tag{6}$$

A is scale factor, unit of wind speed, K is shape factor, dimensionless, v is wind speed in (m/s).

$$P_w=\begin{cases} P_r\cdot\left(\dfrac{v^k-v_{cin}^{\ k}}{v_{rat}^{\ k}-v_{cin}^{\ k}}\right) & \text{if}\quad v_{cin}\le v(t)\le v_{rat} \\ P_r & \text{if}\quad v_{rat}\le v(t)\le v_{cou} \\ 0 & \text{if}\quad v\le v_{cin}\ \text{ or }\ V(t)\ge V_{cou} \end{cases} \tag{7}$$

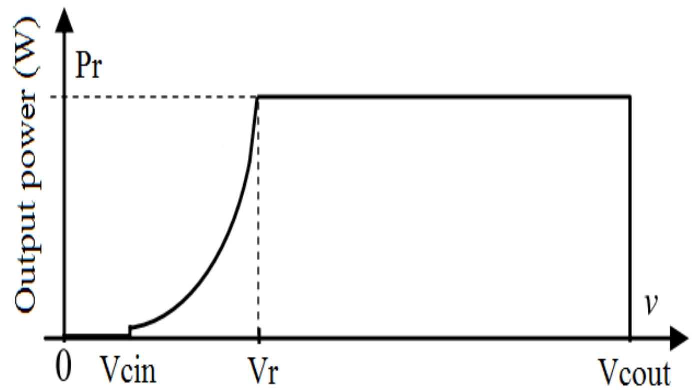

Figure 2. Power curve of a wind turbine.

v_{cin}, v_r and v_{cou} are the cut-in wind speed, rated wind speed and cut-off wind speed given in (m/s). A plot of P_w versus v is shown in Figure *2.*

Substituting Equation 6 and Equation 7 into Equation 5 yields Equation 8 (Johnson, 1985; Borowy and Salameh, 1994)

$$P_{wa}=P_r\cdot\left\{\frac{\exp\left[-\left(\frac{v_{cin}}{A}\right)^k\right]-\exp\left[-\left(\frac{v_r}{A}\right)^k\right]}{\left(\frac{v_r}{A}\right)^k-\left(\frac{v_{cin}}{A}\right)^k}-\exp\left[-\left(\frac{v_{cou}}{A}\right)^k\right]\right\} \tag{8}$$

For small-scale wind turbines, the cut-in wind speed is relatively smaller and wind turbines can operate easily even when wind speed is not very high.

The total power output of the two generators (wind turbine and PV array) is given by Equation 9 (Boudy et al., 2012a).

$$PT=N_{pv}\cdot P_{pv}+N_{ag}\cdot P_{wa} \tag{9}$$

N_{pv} and N_{ag} are the total number of solar modules and wind turbines, respectively.

Battery performance model

The nominal capacity of the battery is modeled using Equation 10 (Borowy et al., 1996):

$$\varphi_r=\frac{N_{bt}}{N_{bs}}\cdot\varphi_{bt} \tag{10}$$

Where N_{bt} is the total number of batteries, N_{bs} is the number of batteries in series, φ_{bt} is the nominal capacity (Ah) of one battery.

During the charging process, the available battery capacity at time t can be calculated by Equation 11 (Koutroulis et al., 2006):

$$d\varphi=n_{bt}\cdot\frac{P_{bt}}{U}\cdot dt \tag{11}$$

φ is the capacity of the storage system at time t given in (Ah), n_{bt} is the battery charging and discharging efficiency. It is difficult to measure separate charging and discharging efficiency, so manufacturers usually specify roundtrip efficiency. In this paper, the battery charging efficiency is set to 80%, and the discharge efficiency is equal to 100% (Duffo-Lopes et al., 2005).

U (V) is the nominal system operating voltage and P_{bt} is the power received by the battery from generator or requested by the demand.

The minimum battery capacity can be given by Equation 12 (Abdelhamid et al., 2011):

$$\varphi_{\min} = \varphi_r \cdot (1 - Pd) \tag{12}$$

Where φ_r is the nominal battery capacity and Pd is the depth of battery discharge.

Regulator performance model

The solar regulator which monitors the load and the battery discharge is dimensioned according to its input current, which is given by the Equation 13 (Boudy et al., 2012a).

$$I_{rg} = \frac{N_{pv} \cdot P_{pv}}{N_{pvs} \cdot n_{rg} \cdot U} \tag{13}$$

N_{pv} is the total number of PV modules, N_{pvs} is the number of PV modules in series, n_{rg} (%) is the regulator efficiency.

Inverter performance model

The inverter is a device which converts DC current of DC bus to an AC current for AC loads.

The power transiting the inverter to serve the demand is given by Equation 14 (Boudy et al., 2012a).

$$P_{in} = \frac{P_{ch}}{n_{in}} \tag{14}$$

n_{in} is the inverter efficiency specified by the manufacturer (%), P_{ch} is the instantaneous demand (W).

Economic model based on the annualized cost system (ACS) concept

The energy optimization of a hybrid system can be done by using an economic criterion. We should introduce an objective function for the various system components. It is a question in our case of establishing a function cost which includes the replacement (C_{rap}), maintenance (C_{main}) and capital cost (C_{cap}) of each component. The Equation 15 gives the function cost of the system.

$$g(x) = C_{cap}(x) + C_{main}(x) + C_{rep}(x) \tag{15}$$

x= [N_{pv} N_{al}, N_{bt}, N_{rg}, N_{in}] is the vector of decision

Annualized capital cost

The annualized cost of each component (PV array, Wind turbine, battery, regulator and inverter) is calculated using Equation 16.

$$C_{acap}(x) = C_{cap}(x) \cdot CRF(i, Y_{proj}) \tag{16}$$

Y_{proj} is the component lifetime (year) and CRF is the capital recovery factor, a ratio to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is given by the Equation 17.

$$CRF(i, Y_{proj}) = \frac{i \cdot (1+i)^{Y_{proj}}}{(1+i)^{Y_{proj}} - 1} \tag{17}$$

The annual real interest rate i is related to the nominal interest rate i' and the annual inflation rate $\inf$ by the Equation 18.

$$i = \frac{i' - \inf}{1 + \inf} \tag{18}$$

Annualized maintenance cost

The system maintenance cost, which has taken the inflation rate (inf) into a count, is given as showing in Equation 19.

$$C_{amain}(Y_{pyoj}) = C_{main}(x) \cdot (1 + \inf)^{Y_{proj}} \tag{19}$$

Where: C_{amain} is the maintenance cost of the Y_{proj} th year.

Annualized replacement cost

The annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project. In the hybrid system under study, only the battery, regulator and inverter need to be replaced periodically during the project lifetime.

$$C_{arep} = C_{rep}(x) \cdot SFF(i, Y_{comp}) \tag{20}$$

Y_{comp} is the components (batteries, regulators and inverters) lifetime (year); SFF is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. The equation for the sinking fund factor is:

$$SFF(i, Y_{comp}) = \frac{i}{(1+i)^{Y_{comp}} - 1} \tag{21}$$

System optimization model with genetic algorithm

The minimization of ACS function is implemented employing genetic algorithm (GA) developed by Leyland (Leyland, 2002; Molyneaux, 2002). This multi objective optimization tool was designed for the optimization of the energy systems, which are

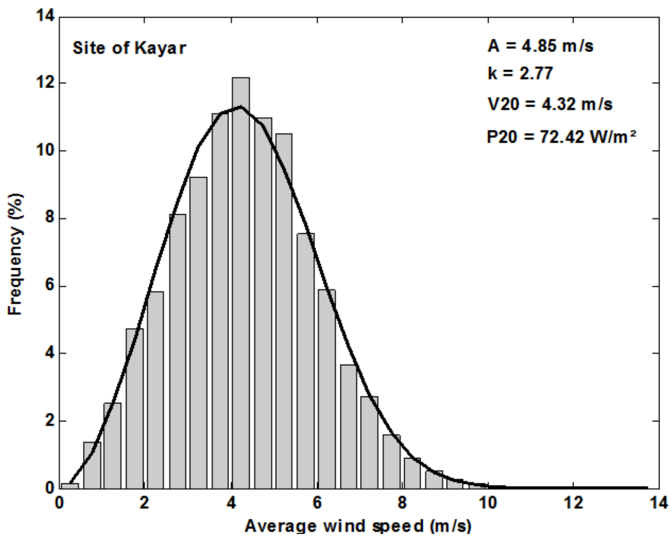

Figure 3. Real and Weibull distribution on the site of Kayar.

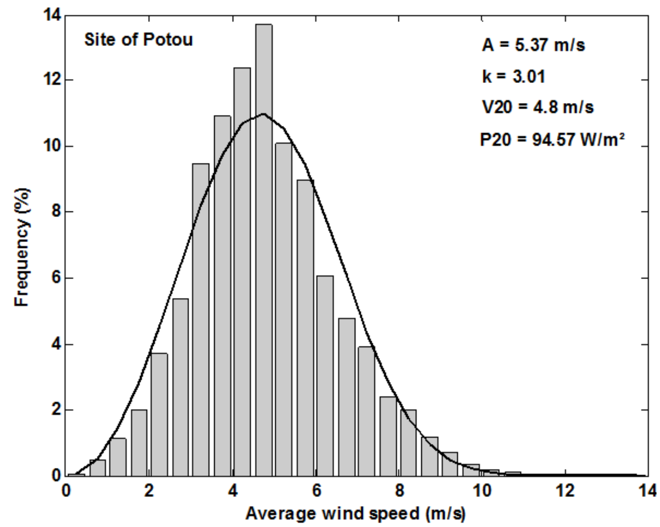

Figure 4. Real and Weibull distribution on the site of Potou.

generally non-linear and uses a statistical technique of grouping of the individual basis on the independent variable (creation of the families which evolves in independent manner). This method has the advantage of maintaining the diversity of the population and of making the optimal algorithm coverage even difficult to find (Sambou, 2008). Further, this method is not restricted by local optimum; it can find the global optimum system configuration with relative computational simplicity compared to conventional optimization methods such as dynamic programming and gradient techniques (Zhou et al., 2010). Furthermore, in a nonlinear multi-objectives optimization problem, there is such a balance that we cannot improve one criterion without deteriorating at least one of others. This balance is called Pareto optimal.

The hourly data used in the model are the solar radiation on horizontal surface, ambient air temperature, wind speed and load demand consumption on an annual basis.

The PV array and the wind turbine outputs are calculated according to the PV and the Wind turbine system model by using the specifications of the PV module and the wind turbine, as well as the solar radiation and the wind speed data. The battery bank with the total nominal capacity φ_r is permitted to discharge up to a limit defined by the maximum depth of discharge Pd.

The initial assumption of system configuration will be subject to the following inequalities constraints (Boudy et al., 2012a):

$$\begin{cases} \varphi_{\min} \leq \varphi \leq \varphi_{\max} = \varphi_{\mathrm{r}} \\ \mathrm{I}_{\mathrm{rg}} \leq \mathrm{I}_{\mathrm{rrg}} \\ \mathrm{P}_{\mathrm{ond}} \leq \mathrm{P}_{\mathrm{rond}} \end{cases} \tag{22}$$

I_{rrg} is the nominal current of the designed regulators (A), φ is the capacity of the batteries (Ah), $\varphi_{\min}$ is the minimum capacity of the batteries (Ah), P_{rond} is the rated power of the inverter (W).

Application on the sites of Kayar and Potou

Presentation of the sites

The sites, Kayar and Potou are located in the cost northwestern of Senegal in West Africa. This zone is characterized by wind potential adapted to small wind turbines (2 to 10 kW) (Boudy, 2005; Youm et al., 2005; Kebe et al. 2008; Boudy et al., 2008, 2010b, 2011, 2012b) on one hand and on the other hand, this zone is characterized by good solar irradiation (Boudy et al., 2007; Drame et al., 2012).

Figures 3 and 4 present the real and theoretical distribution of Weibull of the wind speed on one hand and on the other hand Figure 5 presents the profile of the irradiance on average over the one day respectively in the two sites (Potou and Kayar). It is noted that, the density of wind power is larger (95 W/m²) on the site of Potou than on the site of Kayar (72 W/m²). Then the wind potential is larger on the site of Potou than on the site of Kayar. However, the average daily value of solar radiation is more significant on the site of Kayar (4.4 kWh/m²/d) than on the site of Potou (3.9 kWh/m²/d).

To study the effect of changes in load profiles on the optimal configuration, three types of loads having the same quantity of energy (94 kWh/d) (Figure 6) were used.

Profile 1 gives the load of a village whose fluctuation during the day corresponds to the operation of public equipment (refrigerators, domestic mill, welding machines, and other equipment). The peak of the demand observed at night corresponds to the use of the domestic equipment and some commercial equipment. It can be observed that the power is constant between 5 a.m. and 5 p.m. for load profile 2. This corresponds to the operation of a desalination and water pumping system, commercial refrigerators and domestic equipment, etc. The peak of the power demand observed during the night is due to the domestic equipment (lighting, refrigeration and television. etc.) and the desalination and water pumping system.

Load profile 3 illustrates low consumption during the day (population working in the fields in the morning), and high power demand in the night due to the use of lighting, TV plus the previous consumption (desalination and water pumping system, commercial refrigerators, etc.).

Components characteristics

The specifications of the components used in this study are presented in Table 1.

RESULTS AND DISCUSSION

The methodology presented above was applied on the

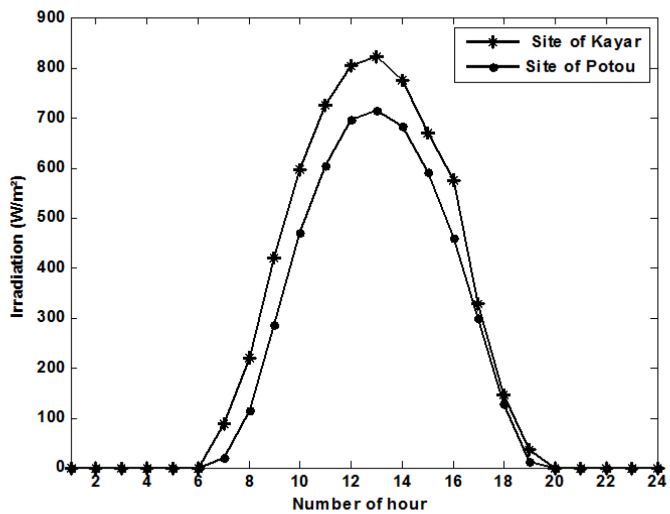

Figure 5. Profile of irradiation on Kayar and Potou.

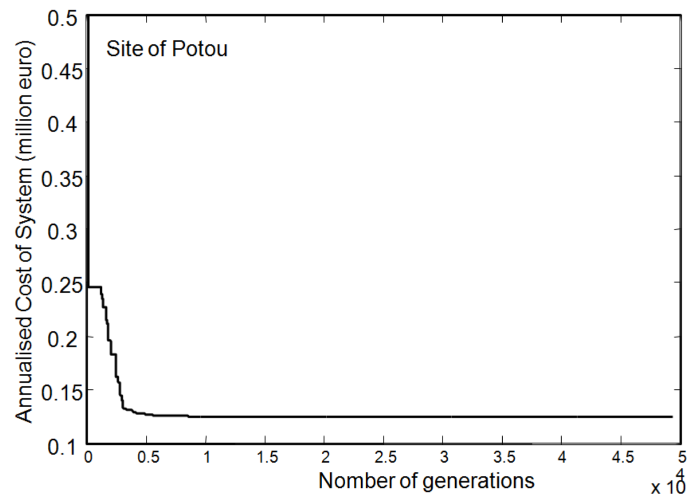

Figure 7. System total cost during AG optimization (Potou).

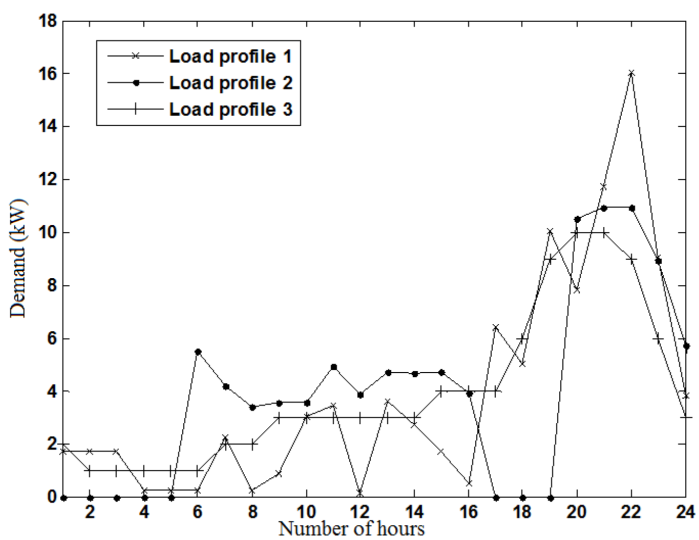

Figure 6. Various profiles of load.

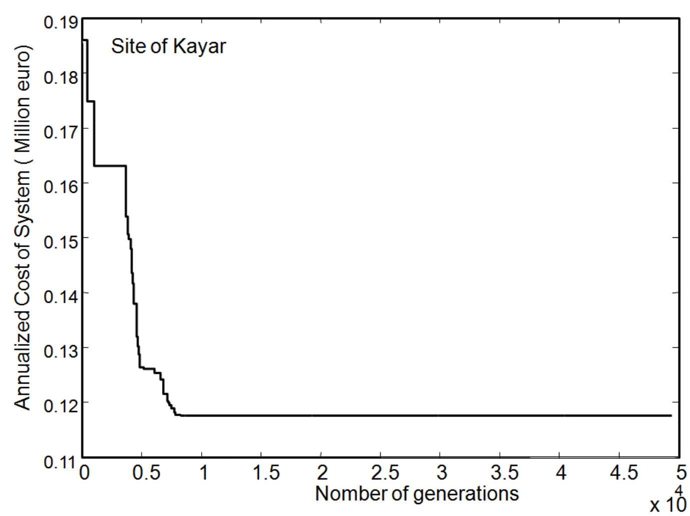

Figure 8. System total cost during AG optimization (Kayar).

two sites (Kayar and Potou) to size an optimal hybrid systems solar-wind-battery for decentralized electrification. The results obtained are presented in two forms:

1. Influence of the potentials on the optimal configuration,
2. Influence of load profiles on the optimal configuration.

Figure 7 and Figure 8 depict the total Annualized Cost of System (ACS) during the processing of optimization in Kayar and Potou respectively using load profile 1. It can be noted that from a configuration, the cost of the following configurations is constant. The optimal configuration for each load profile was computed (Table 2). The studies of the performance of the system have been achieved determining the state of charge of batteries on sites Potou and Kayar (Figure 9). Figure 10 gives the state of charge on batteries for each load profile using the solar and the wind potential of the site of Potou.

Influence of variation of the potential on the optimal configuration

The results of sizing are summarized in Table 2. For the two sites Potou and Kayar, the optimal configuration is a hybrid system with a request of the wind turbines for Potou and a request of the PV modules for the site of Kayar. That can be explained by the fact that, the wind potential is more favorable on Potou and the solar potential is more favorable on the site of Kayar. Further, the diurnal variation of the load profile is more suitable to the diurnal variation of the solar radiation in the site of Kayar than in the site of Potou. However the fraction of the output energy from the wind turbines is higher than

Table 2. Influence of the wind and solar potential on the cost of optimal configuration.

Site	Load profile	Number of PV module	Number of Wind turbine	Number of battery	Number of regulator	Number of inverter	ACS (Million euro)	Total production (kWh)	Percent of wind turbine production (%)	Percent of PV array production (%)
	1	110	41	160	7	6	0,134	55638	71	19
Potou	2	106	43	140	7	4	0,125	52973	73	17
	3	106	40	148	7	4	0,126	53118	72	18
	1	120	41	124	8	6	0.124	51365	64	36
Kayar	2	130	32	108	8	4	0.120	45662	56	44
	3	120	37	116	8	4	0.121	48149	62	38

the fraction of the output energy from the PV modules that is observed for all the sites and for all used load profiles (Table 2).

We can also notice that the annualized cost of system (ACS) is higher for Potou compared to the cost of system for the site of Kayar, that is, because the load profiles used are better suited to the output energy in Kayar than in the site of Potou. So the systems requesting for more size of battery for the site of Potou, resulted in a higher Annualized Cost of System (ACS). The wind turbine sized on Potou and Kayar intervene more during the day time. The calculated battery makes the help rendered to the system more possible the moment the wind turbines and the PV modules cannot produce sufficient energy.

For the load profile n°1, the capacity of storage system dimensioned increases by 25% for Potou compared to the capacity of storage sized for Kayar. This is due to the over-sizing of batteries in the site of Potou. This storage system has to cover the peak of power called by the demand during the night time. However, these batteries will function only a little over their lifetime. That can add the lifetime of the battery bank. The state of charge of the battery bank sized for Kayar and Potou by using load profile n°1 is depicted by the Figure 9. It can be noted that the minimum state of charge of the battery bank is equal to 50% for the two sites. It can be noted, further, that a high frequency is observed for the battery bank charged (state of charge 100%). This is observed for the two sites.

Influence of variation of the load profile shape on the optimal configuration

The study of the influence of the load profiles shape on the optimal configuration was carried out for the site of Potou and Kayar. The optimal configurations obtained are illustrated by Table 2.

It is observed that the fraction of output energy from the wind turbines is higher than 50% of the total output energy for all configurations obtained (Table 2). This remark follows that, the wind turbine used for sizing is well adapted to the wind potential and to the load profiles of demand. The application of sizing, by using the load profile n°2 and n°3, shows a reduction in the number of the batteries compared to the load profile n°1. This is because the load profiles n°2 and n°3 are more adapted to the output energy from PV modules and the wind turbine together than the load profile n°1. This observation is seen for the two sites Kayar and Potou.

The capacity of batteries increased by 14 and 8% for the load profile n°1 compared to the capacity of batteries obtained by using the load profile n° 2 and n°3 respectively, on the site of Potou. Figure 10 gives the state of charge of batteries over one year for all the loads profiles on the site of Potou. The maximum depth of charge is 50% corresponding to the state of charge of 50%.

CONCLUSION

A methodology to size a stand-alone hybrid PV-Wind-Battery system using a genetic algorithm approach (GA) is proposed in this paper. The used models of the wind turbine, the PV panel and the storage unit composing the hybrid system, were presented.

The optimal design of a hybrid system PV-Wind-Battery with the use of the genetic algorithm approach is carried out for two sites Kayar and Potou located in the northwestern coast of Senegal.

The study of the influence of the wind and solar potential on the optimal configuration was carried out. The results obtained showed an influence of variation of the solar and wind potential on the

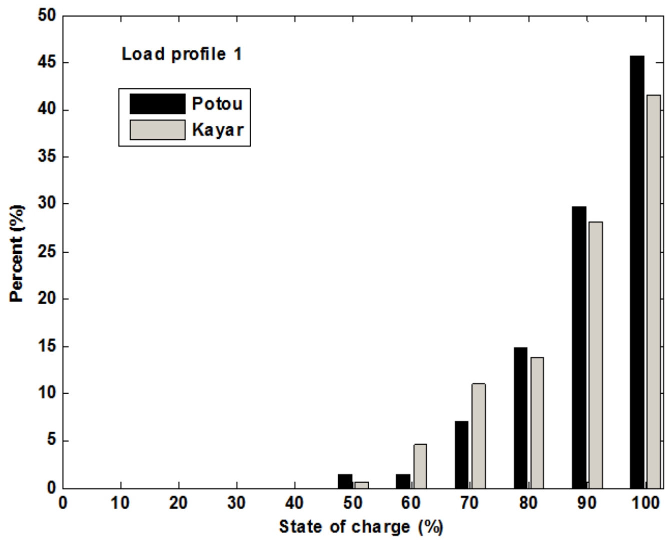

Figure 9. Battery state of charge distribution for the two sites Kayar.

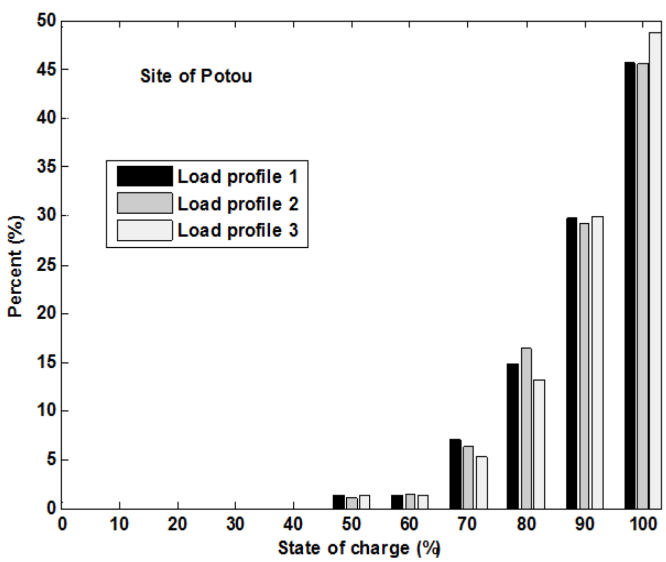

Figure 10. Batteries state of charge distribution for the various profiles of load for the site of Potou.

optimal configuration obtained. For example, for the two sites Potou and Kayar, the optimal configuration is a hybrid system with a request of the wind turbine for Potou and a request of the PV modules for the site of Kayar.

The study of the load profiles influence on the optimal configuration has showed that, the load profile which is suitable for potential fluctuating can reduce the acquisition system cost. On the other hand, it would be interesting to perform the modeling, by incorporating the objectives of availability and reliability constraints of components in order to achieve a more accurate assessment of the cost of ownership system.

NOMENCLATURE

A	scale factor	m/s
C	cost	euro
CRF	capital recovery factor	
FF	fill Factor	
G	global irradiation	W/m²
N	number of components	
NCOT	nominal operating cell temperature	(°C)
P	power	W
Pd	depth of discharge	%
PT	the total power at the output of two generators (wind and solar)	W
SFF	sinking fund factor	

Subscripts:

acap	annualized capital cost
amain	annualized maintenance cost
arep	annualized replacement cost
bt	battery
cin	cut in
comp	components
cout	Cut-offt
cap	initial capital cost
ch	demand
in	inverter
main	initial maintenance cost
max	maximum
min	minimum
oc	open circuit
ocst	open circuit standard
proj	project
pv	photovoltaic
rep	initial replacement cost
rg	regulator
rin	nominal output of inverter
rrg	nominal current of regulator
sc	short circuit
scst	short circuit standard
wa	wind turbine generator

REFERENCES

Abdelhamid K, Maiouf B, Rachid I (2011). Techno-economic valuation and optimization of integrated photovoltaic/wind energy conversion system. Solar Energy, 85: 2407-2420;

Akdag SA, Dinler A (2009). A new method to estimate Weibull parameters for wind energy applications. Energy Conversion Manag., 50: 1761-1766.

Borowy BS, Salameh ZM (1994). Optimum photovoltaic array size for a hybrid Wind/PV system. IEEE Trans. Energy Conversion, 3(3): 482-488.

Borowy BS, Salameh ZM (1996). Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Trans. Energy Conversion, 11: 367-373.

Boudy OB (2005). Etude et modélisation du potentiel éolien du site de Gandon à Saint-Louis : Application au dimensionnement d'une éolienne adapté au site. Master de recherche, p. 63.

Boudy OB, Sambou V, Ndiaye PA, Kébé CMF, Ndongo M (2010a).

Optimal design of a hybrid Solar-Wind-Battery System using the minimization of the annualized cost system and the minimization of the loss of power supply probability (LPSP). Renew. Energy, 35: 2388-2390.
Boudy OB, Ndiaye PA, Kébé CMF, Ndiaye A (2010b). Evaluation du potentiel éolien des sites de Kayar et de Potou Application au choix d'une éolienne adaptée au site. J. des Sci. pour l'Ingénieur.12: 33-41.
Boudy OB, Sambou V, Kébé a CMF, Ndiaye PA, Ndongo M (2012a). Methodology to Size an Optimal Stand-Alone PV/wind/diesel/battery System Minimizing the Levelized cost of Energy and the CO2 Emissions. Energy Procedia, 14: 1636-1647.
Boudy OB, Ndiaye PA, Kebe CM, Sambou V and Ndongo M (2012b). Seasonal assement of wind energy chaeacteristics for electricity generation in the sites of Kayar and Potou Senegal. Rev. CAMES-Série A, 13(1): 9-13.
Boudy OB, Kébé CMF, Sambou V, Ndongo M, Ndiaye PA (2008). Etude et modélisation du potentiel éolien du site de Nouakchott,'' J. des Sci. Pour l'Ingénieur, 9: 28-34.
Boudy OB, Ndongo M, Sambou V, Ndiaye PA, Kebe CM (2011). Diurnal characteristics of the wind potential along the North-western coast of Senegal. Int. J. Phys. Sci., 6(35): 7950-7960.
Boudy OB, Sambou V, Kebe CMF, Ndongo M, Ndiaye PA (2007). Etude et Modélisation du potentiel solaire du site de Nouakchott et de Dakar'' J. Sci., 7(4): 57-66.
Colle S, Abreu SL (2004). Ruther R. Economic evaluation and optimisation of hybrid diesel/photovoltaic systems integrated to electricity grid. Sol. Energy, 76: 295-299.
Drame M, Ould Bilal B, Moctar C, Sambou V, Gaye A (2012). Impacts of aerosols on available solar energy at Mbour. Senegal. J. Renew. Sustain. Energy, 4: 013105.
Duffo-Lopes R, Bernal J, Agustin L (2005). Design and control strategies of PV-Diesel systems using genetic algorithm. Solar Energy, 79: 33-46.
Ekren BY (2008). Size optimization of a PV/wind hybrid energy conversion system with battery storage using response surface methodology. Appl. Energy, 85: 1086-1101.
Johnson GL (1985). Wind Energy Systems. Prentice-Hall, ltic. N.J, Chapter 4.
Justus CG (1978). Wind and System Performance. Franklin Institute Press, Philadelphia.
Kebe CMF, Sambou V, Ould Bilal B, Ndaiye PA et Los M (2008). Evaluation du potentiel éolien du site de Gandon dans la région nord du Sénégal. In CAFMET International Metrology Conference.
Kellogg WD, Nehrir NH, Venkataramanan G, Gerez V (1998). Generation unite sinzing and cost analysis for stand-alone wind, photovoltaïque and hybrid wind/PV systems. IEEE Trans. Energy Conversion, 13(1): 70-75.
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: 1072-1088.
Leyland G (2002). Multi-objective optimization applied to industrial energy problems. These EPFL, n°: 2572 Lausanne.
Molyneaux A (2002). A practical evolutionary method for the multi-objective optimization of complex integrated energy systems including vehicle drive-trains. These EPFL, n°: 2636, Lausanne.
Sambou V (2008). Transferts thermiques instationnaires: vres une optimisation de parois de bâtiments. Thèse, PHASE, Université Paul Sabatier.
Youm I, Sarr J, Sall M, Ndiaye A, Kane MM (2005). Analysis of wind data and wind energy potential a long the northern coast of Senegal. Rev. Energy Renew., 8: 95-108.
Zhou W, Lou C, Li Z, Lu L, Yang H (2010). Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Appl. Energy, 87: 380-389.