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Hybrid Photovoltaic/Wind Energy Systems For Remote Locations

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Abstract

The objective of this paper is to show that a precise study of renewable energy potential is indispensable before implementing a renewable energy system. The solar and wind energy potential is first presented for five sites distributed in a Mediterranean island and the temporal complementarity of these two energy resources is discussed. From this study, two meteorological sites are chosen and we compare the sizing and the profitability of remote hybrid PV/Wind systems for these two special cases study.

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Keywords: PV energy; wind energy; hybrid system; renewable energy potential; optimal sizing; profitability

1. Introduction

In rural areas particularly in the developing world, where most of the population – up to 80% - is located, more than 1 billion people lack the essential energy services to satisfy the most basic needs and to improve their social and economic status. The cost of grid for rural electrification in rural area extension, sometimes very high due to a low density level of population, leads often various organizations to explore alternative solutions. The choice of diesel power generation has been considered for a long time as the most economical and reliable alternative, but this solution is not always the most profitable and induces several environmental and practical nuisances for the user : high operating costs, energy dependence for the user (and for the country), fuel transportation problems, complicated maintenance,

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useful life of 5 years but frequently less due to maintenance problems, no guarantee of uninterrupted generation, sound nuisance and oil waste production.

. A renewable energy system (mainly PV or wind) may be a good solution to supply small and medium energy loads. It can provide an uninterrupted supply of electricity (particularly attractive for systems as telecommunications, security installations, water supply and cooling), it is easy to install and requires a low maintenance and has a high reliability. It has been proved that these systems are often more profitable than other electrification solutions for rural areas and particularly than an engine generators utilization.

Solar energy system cannot provide a continuous source of energy due to the low availability during no-sun period and during winter. The wind system cannot satisfy constant load due to different magnitude of wind speed from one hour to another. So there are big problems in the separately use of these energy sources [1].

In order to achieve the high energy availability required in some application such as: lighting, remote areas electrification and telecommunications, it is necessary to oversize the rating of the generating system. But it is also possible to use hybrid system – combination of two or more renewable energy sources.

In general, the variations/fluctuations of solar and/or wind energy generation do not match the time distribution of the load demand on a continuous basis. But the association of these two random sources allows to view to achieve a high availability and generally to reduce the energy storage size conducing to a lower electricity generation cost [2]. Nevertheless, the elaboration of such an hybrid system is accompanied by problems regarding the design as:

- the choice of the correct size of each component;
- the economical optimisation of the kWh production cost.
- From a case study applied in 5 locations situated in Corsica, we will show how the solar and wind energy resources characteristics influence the sizing and the profitability of such wind/PV hybrid system for remote applications.

2. Sites Description and Renewable Energy Potential

2.1. Presentation of the Five Meteorological Sites

With its 8680 km² and an average altitude of 568 meters, Corsica is the smallest, but the most mountainous of the three big occidental Mediterranean islands (Fig. 1.) (183 km long from 41°19' to 43° North, and 83.5 km large from 6°31' to 7°13 East). Mediterranean by its situation, Corsica is alpine by its structure. As 10 mountains exceed 2,000 m, it is described as "a mountain in the sea". Corsica has more than 1,000 km of coastal area. Thus, there are large differences of temperatures and precipitations: the maritime Mediterranean climate on the littoral and into low valleys and the moderate precipitations (from 600 mm to 800 mm per year) change quite rapidly for the worse as the altitude gets higher. The alpine climate is characterised by greater thermal gradients and profuse precipitations (from 800 mm to 2000 mm per year) in rain or snow forms.

We analyze the renewable energy potential of 5 locations: Ajaccio, Calvi, Ersa, Figari and Solenzara (Fig. 1.). Average hourly values for wind speed and horizontal solar irradiations are used for this analysis; these average hourly values are calculated on 3 or 5 years.

Fig. 1. Position of the Corsican Island and geographical coordinates of the 5 sites

2.2. Solar Potential

We plotted, in Fig. 2, the monthly mean values of daily horizontal solar irradiations. The 5 sites have almost similar solar potential and monthly distribution. For a good sizing, we need to have hourly data of tilted global solar irradiations because the PV modules are placed at any slope angle, then horizontal solar radiations data must be converted into tilted ones. The total solar radiation on a β titled surface I_β is calculated by [3]:

$$I_\beta = I_{b,\beta} + I_{r,\beta} + I_{d,\beta} \tag{1}$$

where $I_{b,\beta}$, $I_{r,\beta}$ and $I_{d,\beta}$ are the hourly beam, reflected and sky diffuse radiation.

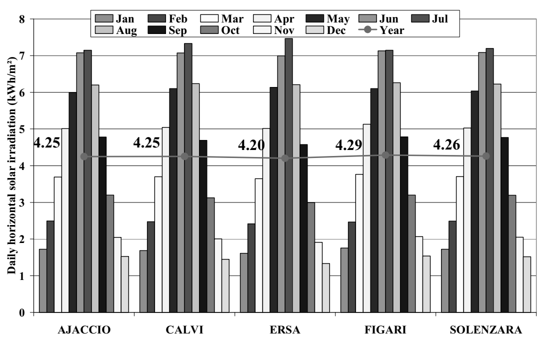


Fig. 2. Daily global Solar Irradiations

To estimate the titled diffuse radiation, successively 2 models were used: CLIMED2 model [4] to calculate the horizontal diffuse component from global one and Klucher model [5] to compute the tilted diffuse radiation from horizontal diffuse. We chose this combination in a previous work [6]. The methodology is illustrated in Fig. 3.

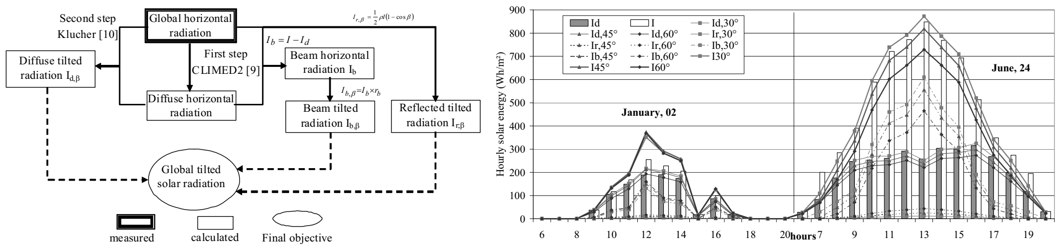
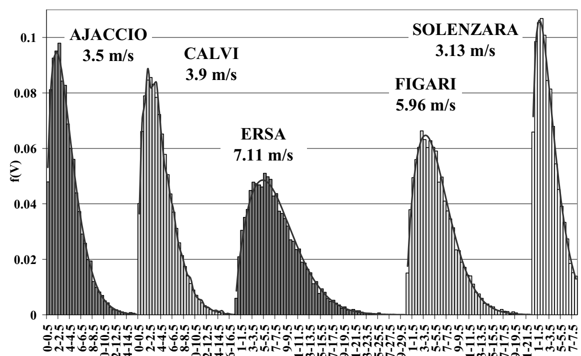


Fig. 3. Method and results : from hourly horizontal global solar irradiations to tilted ones

2.3. Wind Potential

We present the wind potential in term of wind distribution and not in term of wind energy values because it is more usual for a wind potential estimation. Using the Weibull model [7], time series data are analyzed and distributional parameters are estimated for probability distributions on an annual basis. The wind speed distribution and the Weibull distribution are plotted in Fig.4. These sites differ at the same time from energy and distribution point of view making this study more universal.



Station	$\overline{V}$	A	k
Ajaccio	3.50	3.91	1.45
Calvi	3.90	4.35	1.51
Ersa	7.11	8.10	1.72
Figari	5.96	5.94	1.65
Solenzara	3.13	3.46	1.38

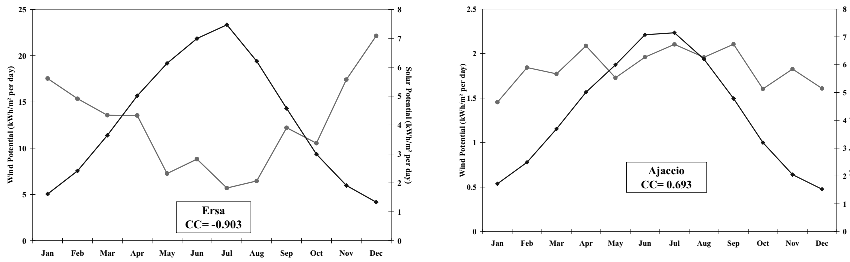
(A: scale parameter (m/s)
k: shape parameter

Fig. 4. Wind distribution, average wind speed and Weibull coefficients

The wind potential variability is high: the average wind speed varies between 3.13 m/s for Solenzara to 7.11 for Ersa and the parameter k is between 1.38 for Solenzara to 1.72 for Ersa.

2.4. Complementarity of the Two Renewable Sources

Our aim is to find out whether solar and wind energy support each other. Amounts of solar radiation per unit area of horizontal surface and amount of wind energy per unit area of blade swept area are compared. To quantify the complementarity quality of renewable resources we use the correlation coefficient (CC) quantifying the simultaneity of solar and wind energy productions. A "good site" has CC near -1. CC is calculated for each station at monthly and daily steps. Ersa has a good monthly complementarity but Ajaccio a bad one (Fig. 5).



Ajaccio	0.693
Calvi	0.571
Ersa	-0.903
Figari	0.455
Solenzara	-0.747

Fig.5. Monthly repartition for Ersa and Ajaccio and CC for each site

Only 2 stations have a negative CC, but only Ersa has a good wind potential (7.11 m/s). We saw the variations of the monthly mean value of hourly wind and solar energy hour per hour throughout the day. In November, we note simultaneity with a high positive CC value, but in January, the 2 productions are nearly in opposite phase (Fig. 6).

In Table 1 are reported the monthly values for each parameters that vary widely according to the site and the month. CC is very rarely negative. The characteristics of the 5 sites are different from an energy point of view and from a temporal repartition of the wind and solar sources; such differences will have am impact on the sizing of the hybrid wind/PV system.

Table 1. CC values for hourly repartition

	1	2	3	4	5	6	7	8	9	10	11	12	Year
Ajaccio	0.21	0.56	0.29	0.65	0.71	0.55	0.48	0.47	0.34	0.54	0.39	-0.10	0.50
Calvi	-0.11	0.64	0.18	0.78	0.77	0.58	0.49	0.51	0.34	0.68	0.49	0.14	0.60
Ersa	-0.27	0.52	0.14	0.67	0.85	0.47	0.51	0.57	0.20	0.53	0.94	0.32	0.63
Figari	0.04	0.62	0.01	0.68	0.87	0.51	0.56	0.52	0.26	0.57	0.79	0.27	0.61
Solenzara	0.04	0.66	-0.01	0.76	0.84	0.65	0.48	0.52	0.36	0.69	0.34	-0.14	0.58

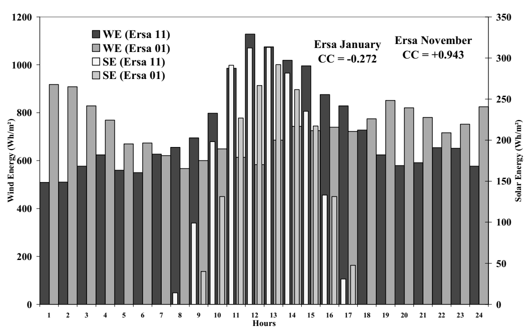


Fig.6. Wind and solar energy daily repartition

3. Presentation of the Wind/PV System

A hybrid PV/wind system (Fig. 7) consists of a PV generator, a wind generator (WT), a battery storage, a DC/DC converter, an AC/DC converter and an inverter able to meet the peak load demand. Here, WT is connected to the load via the AC/DC converter.

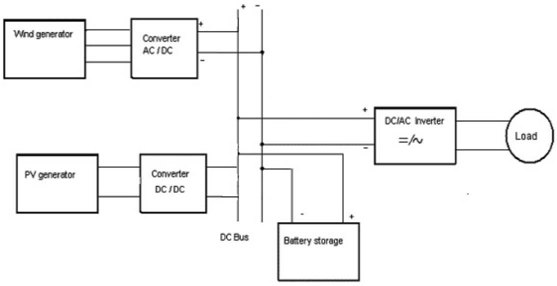


Fig.7. Configuration of the Wind/PV hybrid system

3.1. PV sub-system

The PV generator output is estimated from solar radiation and ambient temperature [13]:

$$P_{PV} = \eta_{PV} A_{PV} I_{\beta} \tag{2}$$

with η_{PV} PV efficiency (Eq. (3)), A_{PV} the PV area (m^2) and I_{β} the solar radiation on titled plane (W/m^2).

$$\eta_{PV} = \eta_{PC} \eta_r \left[1 - \beta\left(T_c - T_{c,r}\right)\right] \tag{3}$$

with η_r reference module efficiency, η_{PC} power conditioning efficiency (= 1 if perfect MPPT), β the temperature coefficient, T_c the cell temperature (°C) [8] and $T_{c,r}$ the reference one.

We have a grid-connected PV system composed of nine 85 Wp m-Si BP585F modules and we present in Fig.8 The experimental validation of the previous model for two days (clear and cloudy skies) using as input data the solar irradiance and the ambient temperature.

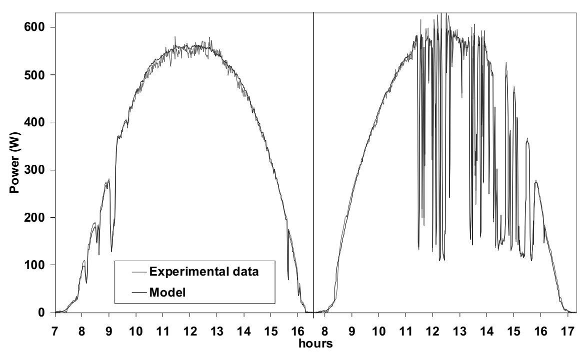


Fig.8. Experimental verification of Eqs (2) and (3)

3.2. Wind Turbine

A study on the influence of the power profile of small wind turbine on its production and on the resulting sizing has been realized previously 9-10]. In this paper, the WT power output is approximated by a quadratic equation as follows [11] and shown in Fig.9:

$$P_{WT} = P^0_{WT}\left[\left(v^2 - v^2_{c,in}\right)/\left(v^2_{rat} - v^2_{c,in}\right)\right] \; for \; v_{c,in} < v < v_{rat};$$

$$P_{WT} = P^{\circ}_{WT} \; for \; v_{rat} < v < v_{c,out};$$

$$P_{WT} = 0 \; elsewhere \tag{4}$$

with P°_{WT} the rated power; $v_{c,in}$ and $v_{c,out}$ the cut-in and cut-off wind speeds; v_{rat} the rated wind speed. v at hub height is calculated from wind speed at 10 m by:

$$v = v_{ref}\left(h/h_{ref}\right)^{\alpha} \tag{5}$$

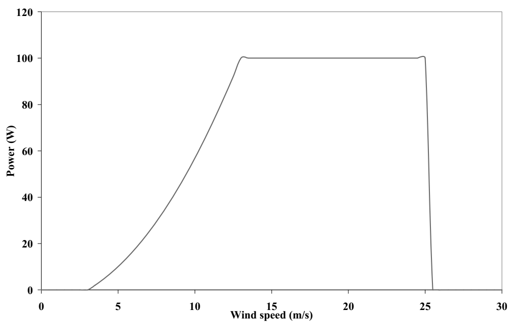


Fig.9: Wind Turbine power profile [11]

3.3. Battery System

Pb-acid batteries are usually used for energy storage in hybrid systems to store surplus energy, to regulate system voltage and to supply load in case of insufficient solar radiation and/or wind. During any hour, the excess power generated by the PV and wind generators can be utilized for charging the batteries whereas the stored energy can be discharged whenever there is a deficiency in power generation: When the power generated, by both the wind turbine and the PV array is insufficient and the storage is depleted, the load will not be satisfied. Therefore, the difference between total energy generated and load demand energy, decides whether battery is in charging or discharging state.

During the charge process, the available battery bank capacity at the time t can be calculated as follows: [12]:

$$C_{bat}(t) = C_{bat}(t-1) + \left[P_{pv}(t)\eta_{DC/DC} + P_{WT}(t)\eta_{AC/DC} - \left(P_{load}/\eta_{DC/AC}\right)\right]\eta_{ch}\Delta t \tag{6}$$

with $C_{bat}(t)$ the battery capacity (Wh) at t, $P_{load}(t)$ the load power, Δt the time step (1h), $\eta_{AC/DC}$, $\eta_{DC/AD}$ and $\eta_{DC/DC}$ the converters efficiencies, η_{ch} the battery charge efficiency ranging from 0.65 to 0.85 [13].

During discharge process, $C_{bat}(t)$ is :

$$C_{bat}(t) = C_{bat}(t-1) + \Delta t \frac{\left(\left(P_{pv}(t)\eta_{DC/DC} + P_{WT}(t)\,\eta_{AC/DC} \right) - \left(\frac{P_{load}(t)}{\eta_{DC/AC}} \right) \right)}{\eta_{dch}} \tag{7}$$

η_{dch} is the battery discharging efficiency taken equal to 1. The battery capacity varies between $C_{bat\,min} \leq C_{bat}(t) \leq C_{bat\,max}$, $C_{bat,min}$ and $C_{bat,max}$ are the minimum and maximum storage capacity with:

$$C_{bat\,min} = DOD.C_{bat,max} \tag{8}$$

DOD is the depth of discharge (generally 70%)

3.4. Electrical Converters

The converters are modeled using their efficiency curve depending on the output power [14].

3.5. Global behaviour of the hybrid system

The hybrid system must be autonomous, it must satisfy the load at every moment. The simulation of the hybrid system behaviour from meteorological data and a daily load profile is based on a global approach using a method based on system energy balance and on a storage continuity. The energy management subsystem is considered ideal: it controls the battery capacity, stops the charge when it reaches $C_{bat,max}$ and interrupts the load when it falls under $C_{bat,min.}$

4. Cost Calculation

The economical approach is based on the LCE determined as the ratio of the total annualized cost of the system to the annual electricity delivered by the system [15]:

$$LCE = TAC / E_{tot} \tag{9}$$

where TAC and E_{tot} represent the total annualized cost and the annual total energy. TAC is calculated by taking into consideration the present value of costs (PVC) and the capital recovery factor (CRF)

$$TAC = PVC \times CRF \tag{10}$$

For a given discount rate, d, and useful lifetime, T, the CRF is defined as [15]:

$$CRF = d(1+d)^T / (1+d)^T - 1 \tag{11}$$

The present value of costs is composed of the initial cost (IC), the present value of maintenance costs (MC) and the present value of replacement cost (RC) [16].

5. Sizing Results

All the results presented here are shown for a typical remote load profile (Fig.10).

In Fig.10, the curves (PV power capacity versus WT power capacity) for 3 days storage capacities are plotted for the 5 sites.

Sizing curves are very different. More specifically, an almost 400% PV generator increase is necessary to guarantee the energy autonomy of the system located at Ajaccio in comparison with that located at Ersa. We show in Fig.11, sizing curves for various storage capacities for lowest and highest renewable potential sites: Ajaccio and Ersa (on the left axis); TAC is also reported on the right axis.

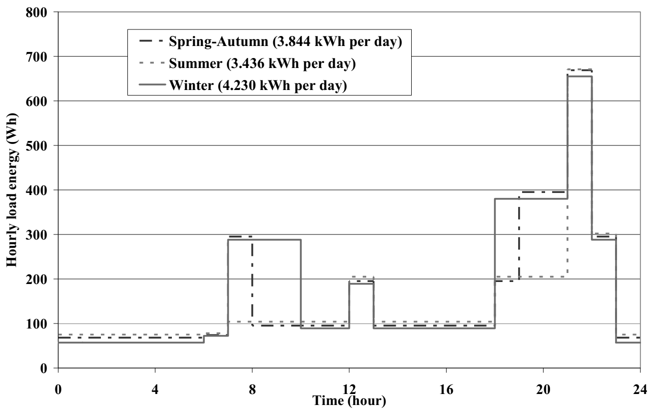


Fig.10. Typical load profile for remote area

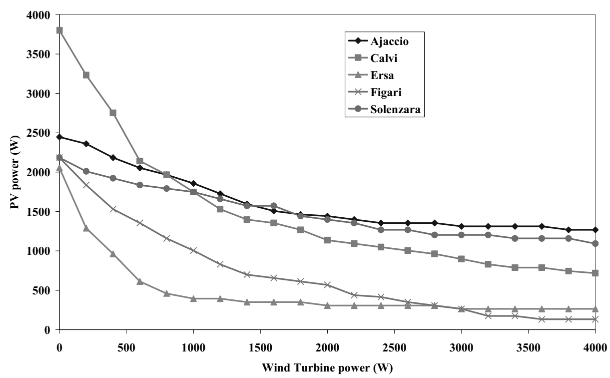


Fig.11. Sizing curves for 3 days storage

For Ajaccio, the optimal configuration is for 3 days storage, against 2 days for Ersa. In Table 2 are presented the optimised results, for wind alone, PV alone and Wind/PV hybrid systems.

We see that:

- the size of the battery decreases when a hybrid system is used what is a high advantage because storage participates for a large part to the system cost as said by Kaldellis et al [17].
- A hybrid system is suitable for Ersa because the LCE is reduced by 35%.
- For Ajaccio, a hybrid system is not justified, the profitability is not improved.
- The difference between the windy and no-windy sites in term of LCE is high.

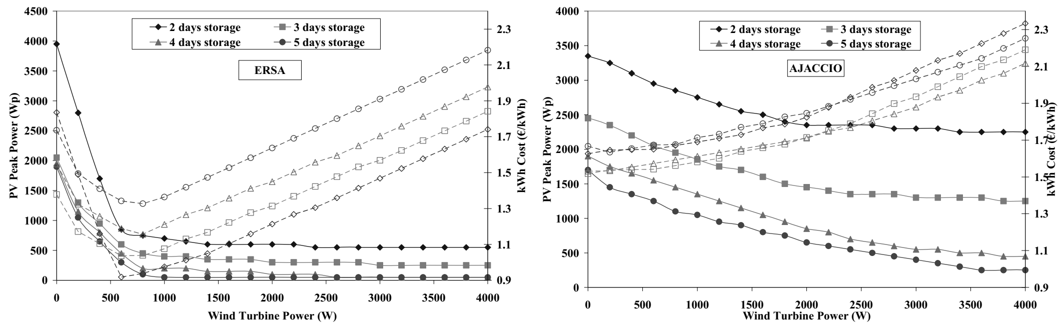


Fig.11. System configurations and LCE

Table 2. Optimization results

Site	Battery size (days)	PV peak power (W)	WT rated power (W)	Levelised kWh cost (€.kWh-1)
PV/Wind Hybrid System				
Ajaccio	3	2350	200	1.54
Ersa	2	850	600	0.92
Wind Alone System				
Ajaccio	6	0	4600	2.54
Ersa	5	0	1200	1.40
PV Alone System				
Ajaccio	3	2450	0	1.52
Ersa	3	2050	0	1.38

Monthly values of PV, WT, excess and load energy are plotted in Fig. 12 for optimised configuration.

Annual renewable energy production is quite identical for each site (Ajaccio:3.8 MWh; Ersa:3.5 MWh), the monthly distribution is more pronounced for Ajaccio than for Ersa due to a better sources complementarity in Ersa. An optimised hybrid system produces 2.5 times more yearly energy than load energy and about 55% of the energy produced is lost. The monthly distribution is different: for Ajaccio between 23% (December) to 70% (July); for Ersa, between 44% (December) to 61% (June). This high excess energy is due to the use of 2 random sources and the necessity to satisfy the load at all times. Increasing LLPS greatly reduces the excess energy [9] and improves the performances. Adding a "controllable" source as an engine generator allows to reach autonomy in reducing energy excess and the size of the other components, with a reduction of the kWh cost.

The battery state of charge (SOC) is analysed for these 2 sites. Fig.13 gives the hourly SOC for these 2 configurations. Due to low wind potential (Ajaccio), SOC is dominated by PV generator power. The smaller SOC occurs on February (between 745 and 1416 h) and December (between 8016 and 8760 h) when production is low, much more power is supplied in spring and summer as indicated by the higher

SOC. In the case of a high wind potential (Ersa), since the important part of energy load requirement is covered by wind energy, SOC varies in large interval and is maintained higher than 0.8 during only summer months (between 3624 and 5832 h), while during other months, SOC is decreased. Using a hybrid system increases the batteries' lifetime remarkably compared to the utilization of either a WT system or a PV system alone, because the charge regime is more appropriate; prolonging the battery lifetime reduces the electricity production costs [18].

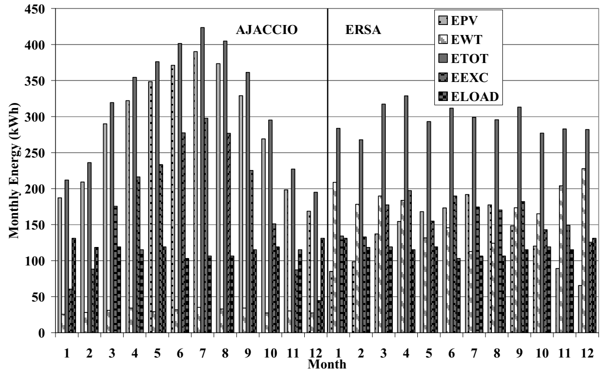


Fig.12. Energy repartition for hybrid configuration

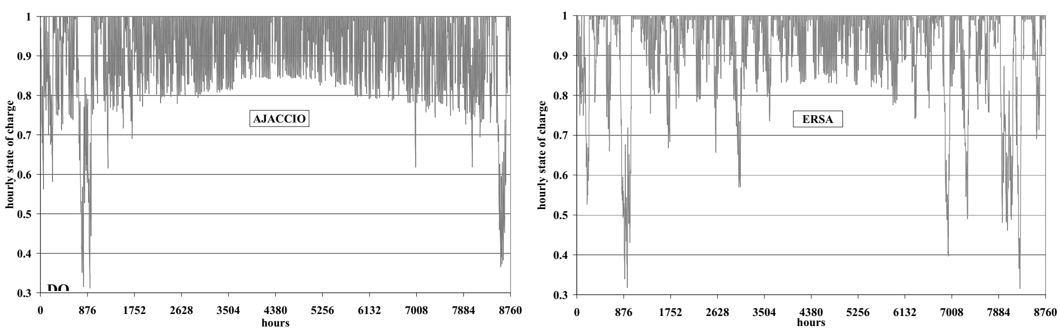


Fig.13. Hourly variation of the battery state of charger for an optimum configuration

6. Conclusion

The objective of the present work is to estimate the optimal dimensions of a stand alone Wind/PV system that guarantees the energy autonomy of a typical remote consumer. We compared the performance for five sites located in Corsica Island and more particularly for a windy and no-windy site. It can be concluded that:

- The LCE depends on the renewable energy potential quality. For windy sites, more than 40% of the total production is provided by the WT, while for no-windy regions, the WT contribution represents only 20% of total production energy.
- Since the five sites have almost the same solar energy potential, the wind energy potential quality affects strongly the LCE.

- The hybrid system is the best option for all the sites considered in this study, yielding lower LCE. Thus, it provides higher system performance than a PV or wind systems alone.
- The choice of the system configuration affects the SOC variation profile, especially at low wind potential sites.
- In all cases, the optimal hybrid PV/wind system, that guarantees a zero LPSP, occurs a high energy surplus. which can reach 75% of the energy production. Therefore, the use of a third controllable energy source (diesel generator) can bring benefit to the system.

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