

# Sizing criteria of hybrid photovoltaic–wind systems with battery storage and self-consumption considering interaction with the grid

Ángel A. Bayod-Rújula<sup>a,\*</sup>, Marta E. Haro-Larrode<sup>a,1</sup>, Amaya Martínez-Gracia<sup>b,2</sup>

<sup>a</sup> Department of Electrical Engineering, CIRCE Research Institute, University of Zaragoza C, María de Luna 3, 50018 Zaragoza, Spain

<sup>b</sup> Department of Mechanical Engineering, CIRCE Research Institute, University of Zaragoza C, María de Luna 5, 50018 Zaragoza, Spain

Received 25 July 2013; received in revised form 1 October 2013; accepted 21 October 2013

Available online 14 November 2013

Communicated by: Associate Editor Mukund Patel

---

## Abstract

The aim of this paper is to analyze the influence of some sizing parameters of grid-connected, hybrid wind-photovoltaic systems provided with energy storage and load consumption, on their interaction with the electrical network. These sizing parameters are the sizing factor (defined as the ratio between the yearly energy produced by the renewable generation system and the yearly energy demanded by a consumer), the solar and wind fractions, and the size of the batteries. The analyzed case study is the supply of energy to a typical residential load in Spain. Annual hourly-based series of energy production from wind and photovoltaic installations in operation in Aragon (an eastern region of Spain) are used as data inputs to a Matlab model of the system. Yearly energy balances for hybrid systems with different combinations and sizes of photovoltaic (PV) plant and wind energy conversion system (WECS) plus Battery Storage Systems (BES) are simulated in an hourly basis. These hybrid systems can inject or absorb energy from the grid depending on whether the energy produced is higher or lower than the household consumption and their operational limits are not exceeded. The interaction with the grid is evaluated in terms of energy injected in or absorbed from the grid, electrical (Joule) losses in lines and load duration curves (LDCs). Although the problem is case-dependent and the correct sizing of such systems is only possible with the knowledge of generation and consumption profiles, some general criteria can be extracted from the results of this paper. Conclusions are also valid for pure PV or Wind systems.

*Keywords:* Hybrid systems; Photovoltaic and wind energy; Energy losses; Battery energy storage; Grid connection

---

## 1. Introduction

One of the challenges in the near future is to obtain enough clean energy supply that helps to contain global warming effects, to reduce the fossil fuel dependence and to avoid the economic impact from raising oil prices. The use of renewable energy sources (RES) is one of the best ways to ensure that human energy needs are satisfied while solving the previously mentioned problems. Wind energy conversion systems (WECS) and Photovoltaic (PV) systems are called to play a fundamental role in the embedded generation of electricity. They can be used in stand-alone

---

*Abbreviations:* AEA, Annual Energy Absorption; AEI, Annual Energy Injection; BES, Battery Storage Systems; DOD, Depth of Discharge; FIT, Feed in Tariff; GLF, generalized load factor; LDC, load duration curve; NLDC, Net Load Duration Curve; PV, Photovoltaics; RCL, Ratio of Conductor Losses; RES, renewable energy sources; SOC, State-of-Charge; WECS, wind energy conversion system.

\* Corresponding author. Tel.: +34 976 761920; fax: +34 976 762226.

*E-mail addresses:* [aabayod@unizar.es](mailto:aabayod@unizar.es) (Á.A. Bayod-Rújula), [marharo@unizar.es](mailto:marharo@unizar.es) (M.E. Haro-Larrode), [amayamg@unizar.es](mailto:amayamg@unizar.es) (A. Martínez-Gracia).

<sup>1</sup> Tel.: +34 976 761920; fax: +34 976 762226.

<sup>2</sup> Tel.: +34 976 762565.

applications or connected to the grid, usually in distribution networks, providing energy near the point of use, reducing losses in transmission and distribution systems. Emission of greenhouse gases associated to other polluting generation units are avoided as well. Reduction of peak grid demand by grid-connected RES systems is also interesting from a utility's point of view. Many governments such as Germany, Italy, Spain and France, recognize the advantages of RES installations in buildings, providing a favorable legislation with incentives for integrated solutions to compensate the higher upfront cost (Colmenar-Santos et al., 2012; Mulder et al., 2010). New legal regulations for small RES installations encourage consumers to maximize self-consumption by offering better tariffs.

However, the integration of renewable energy generation leads to major challenges for distribution grid operators (Beaudin et al., 2010; Hemdan and Kurrat, 2011; Nykamp et al., 2012; Pecas Lopes et al., 2007). The outputs of the PV and wind generation are not constant and vary with the hour and season. Demand is also largely uncontrollable and variable (Borowy and Salameh, 1994). Wind power and photovoltaic generation can complement each other and some problems caused by their variable nature can be partially overcome by integrating these two energy resources in a proper combination, improving the system efficiency and reliability (Zhou et al., 2010). When an energy system includes two or more energy sources is named hybrid. The use of two different resources together increases the complexity of the system in comparison with single energy systems and makes the hybrid systems more difficult to analyze (Borowy and Salameh, 1996; Celik, 2002).

The problem of variable and unpredictable supply from renewable sources could be solved with the development of good energy-storage systems (Diaf et al., 2007; Kim et al., 2008; Mulder et al., 2010). There are a number of studies about the optimization and sizing of Wind/PV hybrid systems in stand-alone applications (Ai et al., 2003; Bagul et al., 1996; Bakos and Tsagas, 2003; Beyer and Langer, 1996; Celik, 2002, 2003; Diaf et al., 2007, 2008; Eke et al., 2005; Ekren et al., 2009; Hocaoglu et al., 2009; Kaabeche et al., 2011; Kellogg et al., 1996; Luna-Rubio et al., 2012; Markvart, 1996; Morgan et al., 1997; Muselli et al., 1999; Prasad and Natarajan, 2006; Protogeropoulos et al., 1997; Seeling-Hochmuth, 1997; Yang et al., 2007, 2008a,b; Zhou et al., 2010). But there are few studies of grid connected hybrid energy systems. These systems are suitable in self-consumption systems where the main priority of the system is to cater the local energy demand and occasionally to feed the grid with any energy surplus (Kaundinya et al., 2009; Luna-Rubio et al., 2012).

The capacity of the storage device for the systems connected to the grid can be smaller than those designed for stand-alone applications since the grid can be used as a system backup. Energy storage can be a valuable resource for the power system by maximizing the efficient use of renewable energy resources, adding flexibility to electric utilities.

It presents a very important strategic value in future electricity networks: by storing the power from renewable sources during off-peak periods and releasing it at on-peak times, coincident with periods of peak consumer demand, energy storage can transform this low-value, unscheduled power into a schedulable high-value product. The stored energy can be re-exported provided there are no voltage constraints, and it can thus be used to take advantage of fluctuating electricity market prices. By shifting load from peak to off-peak periods, generation cost could be reduced and the utilization of investment improved. The procedure of charging at the off-peak-time and discharging at the load-peak-time is called 'Load Leveling' (Wagner, 1997). On the other hand, it is desirable to shave peak demand in order to defer generation, transmission and distribution equipment upgrades, and reduce or avoid the need to purchase much higher cost generation assets. When peak power (kW) limits are placed in the electricity contract, the electricity bill is reduced by 'shaving' the peaks. Moreover, the electrical losses in the power system are a function of the generation and consumption patterns. Storage could be used to reduce peak flows through cables and transformers, relieving overloaded network components (capacity release and reduction of losses) and enable an increase level of distributed generation to be connected to the existing distribution network.

Energy management strategies have to be developed, in conjunction with a communication path for dispatching, to allow the grid operator to define its special needs depending on the grid situation (Castillo-Cagigal et al., 2011a,b). In the relatively slow process of transition towards real active smart grids, (mainly due to inertia and reluctances of the electrical companies and economic costs), it would be an interesting aim to maximize the renewable energy penetration but minimizing the interaction with the grid. Hence, it is very important to analyze the effect of the size of the generation units and the capacity of the batteries on this interaction with the grid, the peak power injected or absorbed, the electrical losses and the load factors.

This paper presents an analysis of the interaction of hybrid PV-Wind systems plus batteries with the grid, and the study of the best combination of these RES and the size of the battery. The cases of pure PV and pure WECS (plus storage) are also shown. The aim of the paper is to analyze how the hybrid composition of the renewable generator (solar and wind fractions), the sizing factor (defined as the ratio between the yearly energy produced by the RES generator and the yearly energy demanded by a consumer) and the size of the batteries affect the amount of energy injected or absorbed from the grid. For this purpose, a Matlab model of the system has been developed and annual hourly-based series of energy production from real wind and photovoltaic installations have been used as data inputs to the model. The scenery of demand considered has been estimated from the REE (*Red Eléctrica de España*, the sole transmission agent and operator of the Spanish electricity system) hourly summer and winter standard days.

Thus, by simulating the model with these hourly-based series an energy balance has been carried out. Several parameters have been defined and analyzed: the Annual Energy Absorption (AEA) of the system, the Annual Energy Injection (AEI), the Ratio of Conductor Losses (RCL), the generalized load factor (GLF), and the Net Load Duration Curve (NLDC).

## 2. Methodology, modeling and parameters of interest

The considered hybrid generation system is a combination of a photovoltaic (PV) plant and a wind energy conversion system (WECS), plus a battery storage system (BES) which can inject or absorb energy depending on whether the energy produced is higher or lower than the household consumption and their operational limits are not exceeded.

Fig. 1 shows the basic schema for hybrid installations with connection to the grid and energy storage.

The working principles of the model that has been implemented in Matlab are described below. The hourly energy production by the hybrid renewable generator each hour of the year is compared with the household demand and depending on the result of the comparison three different situations can be found:

- If the hourly energy demand is higher than the energy generated in the corresponding hourly interval, the renewable energy production is not enough to supply the demand at this hour of the year. If there is enough energy stored in the battery bank as to supply the uncovered demand, the batteries are discharged in that energy amount. If not enough energy is available in the batteries (there is a shortage of energy in the system), the energy must be absorbed from the grid.

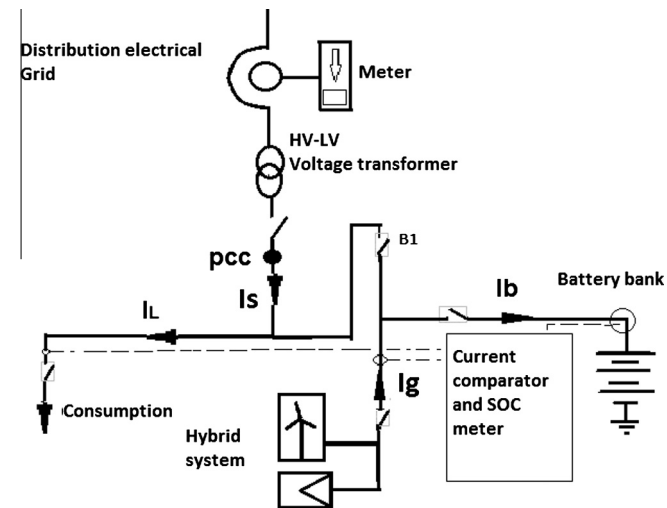


Fig. 1. Scheme of the grid connected hybrid Renewable Energy System plus batteries proposed.

- If the hourly energy demand is lower than the energy generated in the corresponding hourly interval, the demand can be supplied directly by the renewable energy production. If the battery bank is not fully charged, the batteries will be charged in this energy amount. In the opposite case the surplus of energy would be injected to the electrical grid. Depending on the governmental energy policy, this surplus could be sold at a determined price.
- If the energy demand is equal to the energy generated in the corresponding hourly interval, the renewable energy production is enough to supply the demand at this hour of the year, thus the batteries intervention is not necessary. Therefore, the energy generated in this hour is directly delivered to satisfy the energy demand without varying the state of charge of the batteries.

Other special management strategies that allow Energy storage systems combined with renewable energy generation to maximize economic profits (receiving economic signals), to improve some power quality parameters, to produce constant power, etc. are not covered in this paper.

### 2.1. Design parameters

The design parameters that have been used as input data for the analysis of the system are the photovoltaic and wind fractions, the sizing factor  $K$ , and the size of the battery. These parameters are described in the following.

#### 2.1.1. Wind and photovoltaic fractions

Annual hourly-based series of energy production from actual WECS and photovoltaic installations are used as data inputs to the model. By dividing the actual hourly energy production of these installations by their rated size, their productions in per unit of installed power ( $E_{wg,h}$  and  $E_{pv,h}$ , respectively) can be obtained. The wind and photovoltaic energy production are added to obtain the renewable energy production,  $E_{g,h}$  (Wh).

According to Celik (2002), two fractions, the photovoltaic and wind fractions,  $f_{pv}$  and  $f_{wg}$  can be calculated by the following equations (1)–(3).

$$f_{pv} = \frac{E_{pv}}{E_g} \quad (1)$$

$$f_{wg} = \frac{E_{wg}}{E_g} \quad (2)$$

where  $E_{pv}$ ,  $E_{wg}$  and  $E_g$  are respectively the yearly energy generation by the photovoltaic system, the yearly energy generation by the wind generator and the total yearly energy generated in a reference year. The contribution fractions are bounded between 0 and 1 and complementary according to the following equation:

$$f_{wg} = 1 - f_{pv} \quad (3)$$

Let consider  $P_{pv}$  and  $P_{wg}$  the peak power of the PV, and rated power of the WECS. When a photovoltaic (or solar) fraction  $f_{pv}$  is decided,  $P_{wg}$  (W), and photovoltaic power,  $P_{pv}$  ( $W_p$ ) are determined. They can be calculated from the following equations:

$$f_{pv} = \frac{P_{pv}(W_p) \sum_{h=1}^{8760} E_{pv,h}(\text{p.u.})}{E_g} \quad (4)$$

$$f_{pv} = 1 - \frac{P_{wg}(W) \sum_{h=1}^{8760} E_{wg,h}(\text{p.u.})}{E_g} \quad (5)$$

where  $E_{wg,h}$  (p.u.) and  $E_{pv,h}$  (p.u.) are the hourly energy generated by the wind and pv system in per unit and  $P_{pv}$  and  $P_{wg}$  the peak power of the PV ( $W_p$ ), and rated size of the WECS ( $W$ ), respectively.

### 2.1.2. Sizing factor, $K$

A sizing factor can be defined as the ratio between the yearly energy produced by the (hybrid) generator and the yearly energy demanded by the load,  $E_L$ . For example, a sizing factor of 3 ( $K = 3$ ) means that the energy that is generated during a reference year is three times the energy yearly consumed by the load.

### 2.1.3. Battery size

A very simple model of a battery has been implemented. The nominal size of the battery (capacity),  $E_{\text{battery,max}}$  (Wh), is calculated according to Eq. (6), commonly used in standalone systems:

$$E_{\text{battery,max}}(\text{Wh}) = \frac{110C_t(\text{Wh/day})D}{\text{DOD}(\%)} \quad (6)$$

where  $C_t$  (Wh/day) is the daily average consumption;  $D$  is the number of days of autonomy, i.e., the number of days with average consumption that the hybrid grid-connected installation could work autonomously without radiation or wind resources and without absorbing energy from the grid. In stand-alone applications this factor can vary between 4 and 6 days within rural electrification cases, whereas it may be higher than 10 days in professional applications. In our case, grid-connected hybrid systems, through this parameter the batteries capacity will be varied within the simulations; DOD (%) is the Maximum Depth of Discharge, defined as the maximum discharge that the battery can reach without damages. In lead-acid batteries, this value is usually considered around 70%. The Ni-Cd batteries admit depths of discharge higher than 90%.

The State-of-Charge (SOC) is the percentage of the maximum possible charge that is present inside a rechargeable battery. SOC is normally used when discussing the current state of a battery in use. The units of SOC are percentage points (100% implies a full battery state and 0% the empty state). A control block for the energy management of the batteries that takes into account the State of Charge of the batteries in order to avoid overcharges and over-discharges has been developed. When the value of the

energy generated is lower than the energy required by the load, the battery injects energy to the system if the SOC of the battery is higher than a specified value, in order to avoid over discharge. When the energy generation is higher than the energy demand, the battery can absorb energy until the battery is fully charged. If the batteries are fully charged, although there is a surplus of energy in the system the batteries will not absorb energy and this energy is injected into the grid. An initial SOC of 90% was set at the first hour of the year.  $E_{b,h}$  (Wh) is defined as the energy absorbed by the battery in the hour  $h$ . Negative values of  $E_{b,h}$  mean that the energy is being recovered from the battery.

## 2.2. Energy balance

The hourly energy absorbed from or injected into the grid ( $E_{s,h}$ ) is obtained from the energy balance defined as the algebraic sum of the explained variables:

$$E_{s,h} = E_{L,h} - E_{g,h} + E_{b,h} = E_{L,h} - (E_{pv,h} + E_{wg,h}) + E_{b,h} \quad (7)$$

In order to show the behavior of the different variables along the time, the evolution of  $E_{pv}$ ,  $E_{wg}$  and  $E_L$  (energy generated by the PV system, energy generated by the WECS and energy absorbed by the load, respectively) for a period of three days have been represented in Fig. 2. The result of  $E_L - E_g$  represents the exchange of energy with the grid if no batteries are connected.

The effect of the battery can be seen in Fig. 3 in which the exchange of energy with the grid considering the batteries,  $E_s$ , is shown. Positive values correspond to injection into the grid, and negative values correspond to absorption of energy from the network. Clearly the batteries reduce the interaction with the grid and therefore they reduce the line losses.

It can be seen that while the battery is full, the whole surplus is sold, whereas when it is at the lowest permitted value of SOC, all the demanded energy is absorbed (bought) from the grid.

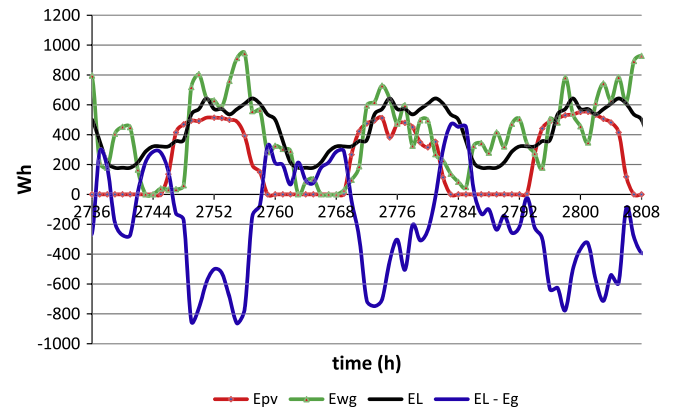


Fig. 2. Evolution of the photovoltaic, wind, load and (load minus generation) energy along three days' time.

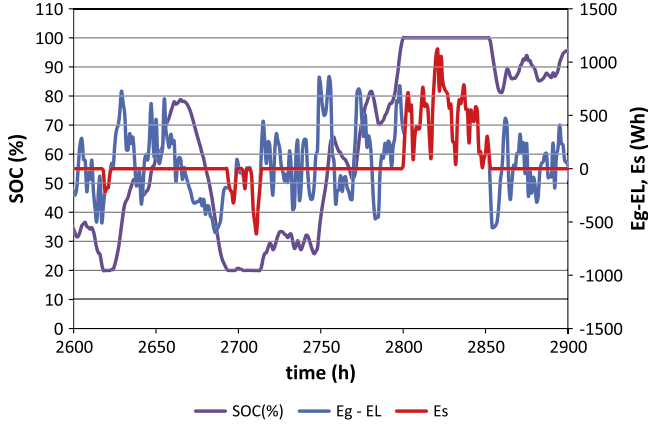


Fig. 3. Dynamic behavior of the hybrid system corresponding to a system with 30% of photovoltaic fraction and a battery size of 12 kW h, and sizing factor  $K = 1$ .

### 2.3. Energy parameters for the analysis

As previously indicated, the parameters defined in this paper for the analysis are the Annual Energy Absorption (AEA), the Annual Energy Injection (AEI), the Ratio of Conductor Losses (RCL), and the Net Load Duration Curve, (NLDC).

The exchange of energy with the grid  $E_s$  (Wh), is split into their positive and negative values in order to separately calculate the surplus (energy injected into the grid) and the shortage of energy (energy absorbed from the grid).

The Annual Energy Absorption (AEA) is defined as the sum of all the energy absorbed from the grid (the size of the hybrid system is not enough to feed the load) along the year of the simulation, divided by the annual energy demand:

$$AEA(\%) = \frac{\sum_{h=1}^{8760} |E_{s,h}(E_{s,h} < 0)|}{\sum_{h=1}^{8760} |E_{L,h}|} \times 100 \quad (8)$$

This percentage represents the fraction of the annual demand that the residence owner should buy to the Electric Distribution Company to meet his energy requirements.

Additionally the surplus of energy is accounted for through the Annual Energy Injection (AEI), the accumulation of all energy injected into the grid along the year divided by the annual energy demand:

$$AEI(\%) = \frac{\sum_{h=1}^{8760} |E_{s,h}(E_{s,h} > 0)|}{\sum_{h=1}^{8760} |E_{L,h}|} \times 100 \quad (9)$$

The AEI is the fraction of the annual demand that due to full charged batteries, it is impossible to store and is injected into the grid (in case of a favorable legislation, this energy is sold at a determined price). With  $K = 1$ , the Annual Energy Absorption equals the Annual Energy Injection.

From the utility point of view, the quantification of the energy loss in conductors, load factor, peak demand and load duration curve result also of high interest.

In inner distribution conductors, in distribution feeder circuits and in transmission lines, some energy losses are produced due to the Joule effect (resistive heating). These energy losses are proportional to the square of the total current flow. Line losses are also proportional to the resistance of the wire, which increases as the wire gets hotter.

Line losses occur not only in the wires, or conductors, but also in transformers and other transmission and distribution system devices. In every case, the loss reductions are location specific. The energy losses in distribution feeders and transformers are also a function of the other demands on the system. The line loss savings will be greatest at those times when the system is most heavily loaded.

In this paper only reduction of losses due to the active component of the currents, in the inner part of the system (conductors connecting load and the point of common coupling with the distribution system) are considered. This is a conservative point of view because the actual reduction of energy losses will be greater.

The Ratio of Conductor Losses in per unit, RCL (p.u.) has been calculated using approximation given by the following equation:

$$\begin{aligned} RCL(p.u.) &= \frac{\sum_{h=1}^{8760} 3 \cdot R \cdot I_{s,h}^2}{\sum_{h=1}^{8760} 3 \cdot R \cdot I_{L,h}^2} = \frac{\sum_{h=1}^{8760} 3 \cdot R \cdot \left(\frac{E_{s,h}}{\sqrt{3} \cdot V \cdot \cos \varphi}\right)^2}{\sum_{h=1}^{8760} 3 \cdot R \cdot \left(\frac{E_{L,h}}{\sqrt{3} \cdot V \cdot \cos \varphi}\right)^2} \\ &= \frac{\sum_{h=1}^{8760} E_{s,h}^2}{\sum_{h=1}^{8760} E_{L,h}^2} \end{aligned} \quad (10)$$

where  $I_{s,h}$  is the intensity of current in the grid ( $I_L - I_g + I_b$  in Fig. 1) (1-h averaged),  $I_{L,h}$  is the intensity of current which flows from the grid to the house if there is no generation system,  $V$  is the voltage at the point of common coupling and  $\cos \varphi$  is the displacement factor of the load. Values of RCL (p.u.) less than 1 mean that losses have been reduced with respect to the case of only consumption (neither generation nor storage). For instance,  $RCL = 0.4$  means that the Joule losses drop to a 40% of the base case.

Load factor is a measure of the degree of uniformity of demand over a period of time, usually one year. It is calculated by dividing the total energy provided by a system during the period by the product of the peak demand during the period and the number of hours in the period. It is equivalent to the ratio of average demand to peak demand expressed as a percentage. A high load factor means power usage is relatively constant. Low load factor shows that occasionally a high demand is set. To service that peak, capacity is sitting idle for long periods, thereby imposing higher costs on the system.

The load duration curve (LDC) is an arrangement of all load levels in a descending order of magnitude. The area under the LDC represents the energy demanded by the system. LDCs are used in electric power generation to illustrate the relationship between power generating capacity requirements and capacity utilization. It shows the percentage (or number) of hours of the year at which the load is at

or above a given value or percentage of peak load. In general, a flatter load-duration curve is better for grid operation, allowing dispatchable generation to run at a higher capacity factor over the entire year and requiring less peaking reserves. The easiest system to operate, for example, would be one with a load-duration curve that is a horizontal line indicating the demand is entirely constant for the whole year. A Net Load Duration Curve (NLDC) can be defined in systems in which the energy can be injected or absorbed from the grid, computing the absolute value of the flux of energy.

### 3. Case study

Load profiles show characteristic daily and seasonal patterns (Fig. 4). For example, most hourly profiles for commercial and institutional facilities rise in the middle of the day and then taper off during early morning and late evening hours.

The scenario of demand considered in this paper has been taken from the REE hourly typical domestic demand (Red Eléctrica de España, 2010). The daily profiles in cold and hot seasons are shown in Fig. 4.

Notice that in winter seasons there is one peak of consumption between 21.00 and 22.00 h corresponding to the high occupation of residences and the critical use of heating and lighting systems. However, in summer the consumer behavior presents two peaks along the day, one corresponding to the noon and another to the evening, as a consequence of air conditionings use and household appliances. The absolute value of energy demand in a winter day is higher than the one corresponding to a summer day. The yearly energy consumption is 4000 kW h/year (average household consumption in Spain) and the load factor is 0.5112.

Hourly series of wind and photovoltaic energy production has been provided by the owners of a wind farm and a PV installation located in Aragon (Spain). Obviously the photovoltaic production is null during the night periods and bigger in summer than in winter. On the other hand, the energy production generated by the wind turbine is more random, not necessarily null during night periods and usually higher in winter than in summer. By multiplying these series in per unit times the installed wind and photovoltaic power precalculated according to the hybrid compositions predefined, the hourly series are obtained (in W h).

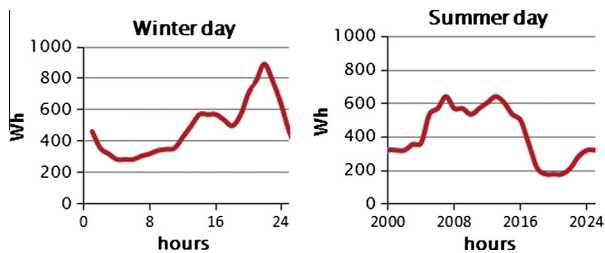


Fig. 4. Residential daily profile in winter and summer.

The amount of energy that a generation system produces as a fraction of the amount of energy that could have been processed if it were operated at its rated capacity for the entire year is called capacity factor. In this case, the capacity factor for the WECS is 0.27, and for the PV system is 0.22. In hybrid installations, depending on the PV fraction, a different capacity factor is obtained.

It is very convenient to start the energy analysis with the case of the hybrid generator sized to supply an annual amount of energy equal to the annual demand (4000 kW h,  $K = 1$ ). For this requirement (annual energy generated by the hybrid system equals the annual demand) the installed photovoltaic and wind power within the different hybrid percentages are shown in Fig. 5:

Fig. 5 shows that depending on the photovoltaic fraction the photovoltaic power ranges from 0 to 2.2 kWp and the wind power between 0 and 1.6 kW, being the bounds the non-hybrid cases. With the current prices of PV and small wind systems, high values of PV fraction would be preferred from an economic point of view in most of the electricity markets with Feed in Tariff systems. Nevertheless, this paper focuses in the energy interaction with the grid, not in economy considerations.

These sizes of the photovoltaic and wind generator are considered as data input to simulate the energy balance of the hybrid model, for each case of hybrid percentages of wind and photovoltaic contributions.

### 4. Analysis of results

In this section, the analysis of the different parameters of interest in the case study described in section 3 is presented.

#### 4.1. Annual Energy Absorption and Annual Energy Injection

It has to be noticed that although the hybrid generator is sized to entirely cover the annual demand, at certain time intervals of the year the energy production exceeds the energy demand, and the surplus of energy would be stored if a remain capacity is available in the batteries or injected into the electrical grid; In other time intervals of the year, the energy production may be lower than the energy

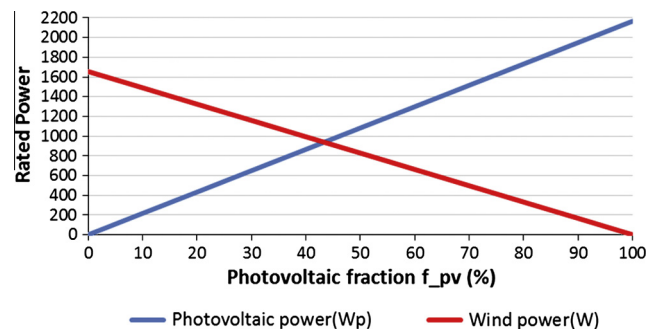


Fig. 5. Installed photovoltaic and wind power versus photovoltaic fraction.

demand and in that case the energy stored would be used until reach the maximum deep of discharge, and then the energy has to be absorbed from the electric utility.

The AEA obtained for  $K = 1$  with different values of photovoltaic fraction and different days of autonomy is presented in Fig. 6.

In PV-Wind systems without batteries, ( $D = 0$ ), a high percentage of the annual demand must be bought from the grid. In pure wind systems, this percentage is nearly 50% (49.02%) and in a pure PV system the percentage is nearly 60% (58.26%). In an hybrid system with a photovoltaic fraction of around 40%, the energy shortage is reduced to 35% of the annual demand, showing the complementarity of both sources.

The addition of batteries implies a lower need of absorption of energy from the grid. Notice that without batteries, the energy absorbed from the grid in a wind pure systems is less than in pure photovoltaic systems. However, with a battery, the need of energy absorption is less with pure pv systems. For instance, with  $D = 1$ , 33% of the total energy must be absorbed from the grid with a wind generator, but only a 21% is required with a pure photovoltaic system. This is due to the better coincidence in time of the solar generation and the load demand.

Again, it can be seen that hybrid configurations are better attending to the need of energy absorption. The best solar fractions with batteries are around 60%. In the case of  $K = 1$  without batteries, the graphs for the AEI as a function of the pv contribution and battery sizes are the same of that of AEA of Fig. 6 (the energy absorbed some hours equals the energy injected other hours). Hence, in the case of pure PV systems the interaction with the grid (exchange of energy, AEA + AEI) is a 20% greater than in the case base (only consumption). Both the shortage and the surplus of energy decrease as the battery size increases and all the curves presents a minimum which varies between the 40% (systems without batteries) and the 60% of the photovoltaic contribution.

The connection of storage reduces greatly the shortage of energy. However, a big capacity is not justified It can be seen that with a capacity of one day of autonomy ( $D = 1$ ), the shortage is reduced to one third of the initial

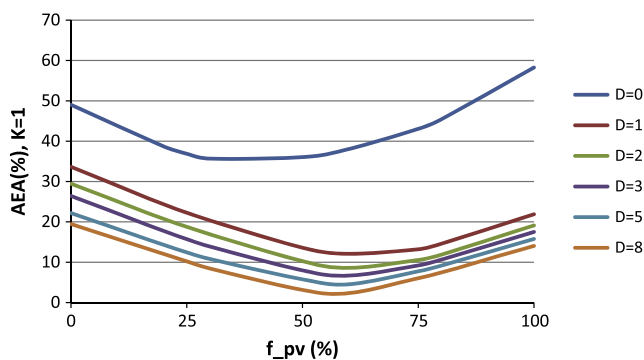


Fig. 6. Annual shortage of energy AEA (%) within the hybrid composition for different battery sizes,  $K = 1$ .

value (from 58% to 21.8% in the pure PV case) but batteries bigger than  $D = 3$  barely achieve greater reduction of the energy absorption.

A possible solution to reduce the AEA, i.e., to reduce the energy bought to the grid would be to increase the size of the generators (values of  $K$  greater than 1). In Fig. 7 the curves of AEA for  $D = 0$  and different hybrid composition factors and sizing factors ( $K = 0.5, 0.9, 1, 2, 3$  and 7) are presented:

Obviously, for values of  $K$  greater than one (oversizing), a reduction in the energy that must be bought to the grid is obtained (the Annual Energy Absorption decreases) but the surplus of energy increases as the generator is more and more oversized. The annual surplus of energy ratios are shown in Fig. 8. In countries with Feed in Tariff (FIT) systems, this situation can be highly profitable. But the current trend is not to pay the energy injected to the network or to pay it only to price of pool. In these cases the oversizing of the generator is not justified.

Adding batteries, the annual absorption of energy is smaller. Hybridation is very convenient if possible (minimum values of AEA are obtained with solar fractions between 25% and 75%). In these cases, no more of 2–3 days of autonomy give values of energy absorption virtually null. With high oversizing factors the shortage of energy is nearly the same for the entire range of pv fraction. It means that this last parameter is less critical within the objective of minimizing the energy shortage.

It has been shown that the flow of energy in the grid varies with  $K$  and  $D$ . The effect in the losses is analyzed in the following section.

#### 4.2. Ratio of Conductor Losses

Simulations show that in systems without storage and  $K > 1$ , losses are higher than in the base case (only demand, without generation or storage). For instance, in pure PV systems, with  $K = 3$ , conductor losses are increased 19 times. With  $K = 1$ , losses with pure pv or pure wind systems are greater than without generation. For instance, in pure pv systems (pv fraction = 100) the losses are 1.69

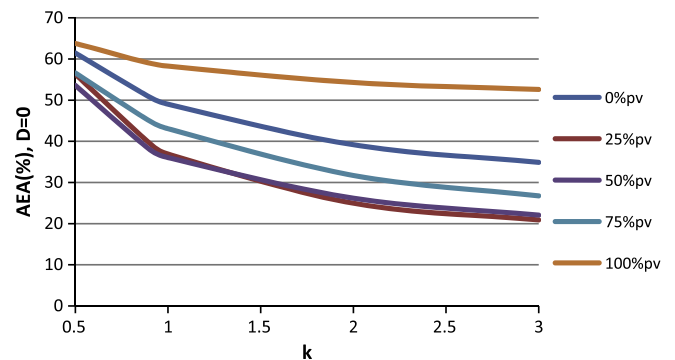


Fig. 7. Annual absorption of energy of various hybrid systems oversized and undersized according to  $k$  factor, without batteries.

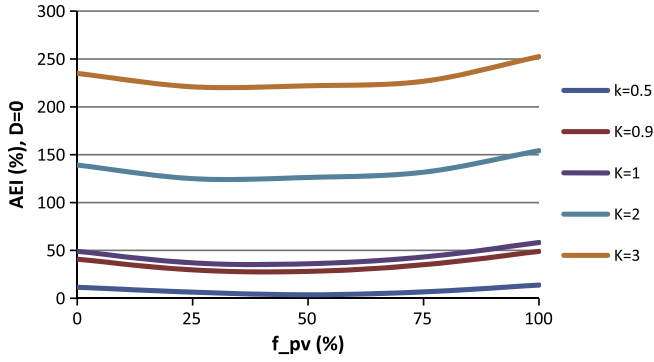


Fig. 8. Annual injection of energy of various hybrid systems oversized and undersized according to  $k$  factor, without batteries.

times bigger (Fig. 9). Only for sizing factor lower than 0.9 losses are better for any pv fraction.

From the point of view of minimization of losses, the best values for the sizing factor are those between 0.5 and 0.7. With  $K = 0.6$  losses are only a 42% when the solar fraction has a value of 50%. For pure wind or pv systems, the optimum value for  $K$  is 0.4.

The connection of batteries is very convenient from a reduction of losses point of view, as it can be seen in Fig. 10 where the case of  $D = 1$  is represented. In this case, the conductor losses are reduce to some above 0.2 for  $K = 0.8-0.9$  (0.35 for pure pv systems and  $K = 0.7$ ).

Again, simulations show that the reduction of losses is less significant as  $D$  increases.

The reduction of flux in lines can also be seen, together with other interesting features, attending the load duration curves.

### 4.3. Load factor

As it has been mentioned, the capacity factor for the WECS in the considered case study is 0.27, and for the PV system is 0.22, and the load factor is 0.51. In hybrid installations, depending on the PV fraction, a different capacity factor is presented. The evolution of the total capacity factor of the hybrid systems in this case is linear, as it is shown in Fig. 11.

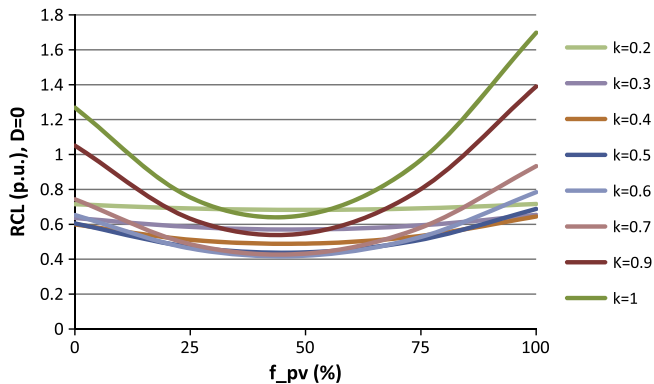


Fig. 9. Ratio of Conductor Losses for different hybrid fractions and sizing factors,  $D = 0$ .

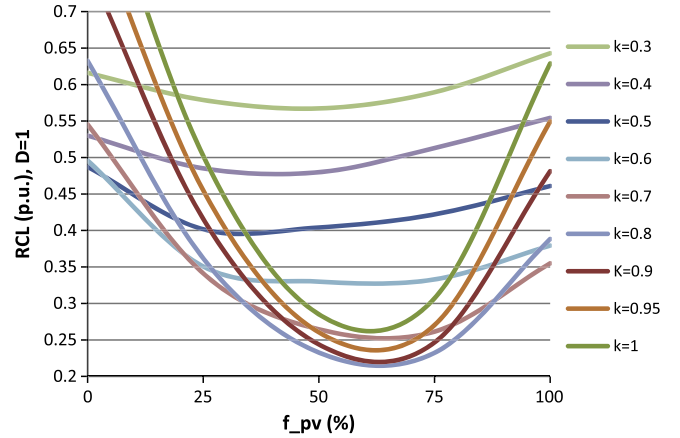


Fig. 10. Ratio of Conductor Losses for various hybrid systems and sizing factors with batteries of 1 day of autonomy.

A generalization of the concept of load factor is used in this paper. The generalized load factor (GLF) of the whole system (load plus generation plus batteries) can be defined as the ratio of average energy along the year to the peak power in the point of common coupling with the grid (pcc in 1). The GLF for  $K = 1$  is represented in Fig. 11. The generalized load factor is dependent on the solar fraction, as the capacity of the battery and the sizing factor  $K$  increases, the final load factor in the lines decreases.

### 4.4. Load duration curves

The load duration curve (LDC) in the case  $K = 1$ ,  $D = 0$  is shown in Fig. 12. In this case the maximum values of power transmitted by the lines (injection of 1496 W) is nearly two times the case base (893 W of peak consumption).

It is perhaps more relevant to represent the Net Load Duration Curve (Fig. 13). In this curve is considered only the magnitude of the flux exchange with the grid.

With values of the sizing factor greater, the peak power injected in the grid is obviously greater. For example, in the case  $K = 2$ ,  $D = 0$ , simulations reveal that peak values of

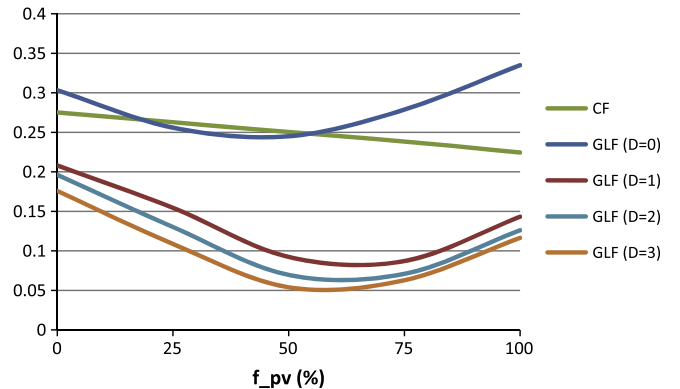


Fig. 11. Capacity factor and generalized load factor versus solar fraction and  $D$ ,  $K = 1$ .

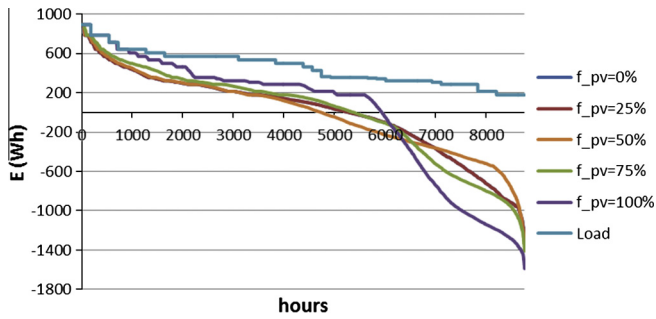


Fig. 12. Gen-Load and load duration curves for different hybrid systems,  $K = 1$ ,  $D = 0$ .

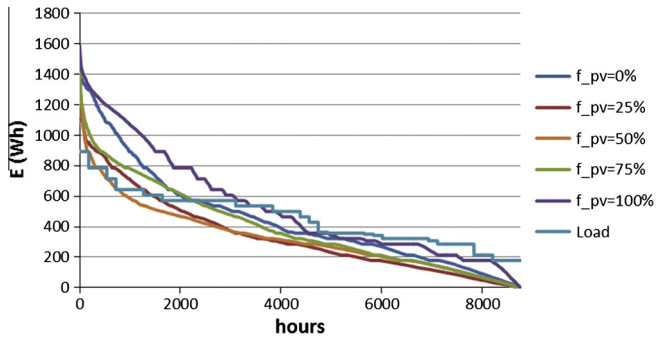


Fig. 13. Net Load Duration Curves for different hybrid systems,  $K = 1$ ,  $D = 0$ .

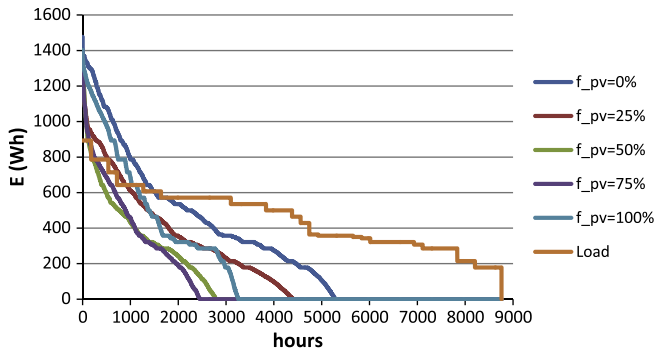


Fig. 14. Net Load Duration Curves for different hybrid systems,  $K = 1$ ,  $D = 1$ .

3540 W are injected, nearly four times bigger than the requirements of peak power of the demand.

Fig. 14 shows the situation of  $K = 1$ ,  $D = 1$ . With the connection of batteries, the peak power is only slightly reduced.

## 5. Conclusions

This paper shows the influence that the size of the elements of a grid-connected hybrid installation with batteries has on different electrical parameters. Some general criteria may be concluded.

Wind power and photovoltaic generation complement each other. The energy analysis establishes that the hybridization of renewable energy systems provides reductions in the annual energy that is necessary to buy to the electrical system in comparison with the non-hybrid systems. In PV-Wind systems without batteries, ( $D = 0$ ), a high percentage of the annual demand must be bought from the grid. In pure wind systems, this percentage is nearly 50% (49.02%) and in a pure PV system the percentage is nearly 60% (58.26%). In an hybrid system with a photovoltaic fraction of around 40%, the energy shortage is reduced to 35% of the annual demand, showing the complementarity of both sources. Besides, the increase of the capacity of the battery and oversizing the generator also contribute to this reduction.

The connection of batteries to the system results in lower values of energy absorption from the grid and energy injection, and thus, lower values of electrical losses in wires. There is not a linear relation between capacity and reduction of losses; the improvement is greater with low values of days of autonomy. With a capacity of one day of autonomy ( $D = 1$ ), the shortage of energy is reduced to one third of the initial value (from 58% to 21.8% in the pure PV case) but batteries bigger than  $D = 3$  barely achieve greater reduction of the energy absorption.

Additionally, in oversized generation systems ( $K > 1$ ) the amount of energy injected into the grid is very high and it only makes sense if the legislation is favorable to the sale of this energy. With small sizing factors, bigger sizes of batteries are required if a low value of shortage of energy (energy absorption from the grid) is desired, what is not economically justified.

The flow of energy in the lines, the associated Joule losses, the influence of the size of the generator and battery and the best combination (solar fraction) in hybrid systems have been also considered. Increasing the sizing factor above 1 implies an increase of electrical losses in the line between the point of common coupling and the generator system due to the increase of the injection to the grid. For instance, in pure PV systems, with  $K = 3$ , conductor losses are increased 19 times. Optimum values are obtained with sizing factors  $K = 0.5$  to 0.7. In the case of pure PV systems of pure wind systems, the lowest values of losses are obtained with  $K = 0.4$ ; without batteries, a 40% of reduction of reduction of losses are obtained respect the case of  $K = 0$  (only consumption in this site). By adding batteries, the reduction of losses is greater. With  $D = 1$  the losses are only a 20% (for values of  $K$  between 0.8 and 1) of the  $K = 0$  case. With pure PV or Wind systems, the final losses are only a 35% of the initial losses.

The generalized load factor is dependent on the solar fraction, and as the capacity of the battery and the sizing factor  $K$  increases, the final load factor in the lines decreases. Finally, it is interesting to note that in oversized generation systems, the peak power is also much higher than in the case of not having in-site generation, with few influence of the size of the batteries.

## References

- Ai, B., Yang, H., Shen, H., Liao, X., 2003. Computer-aided design of PV/wind hybrid System. *Renewable Energy* 28, 1491–1512.
- Bagul, A.D., Salameh, Z.M., Borowy, B., 1996. Sizing of stand-alone hybrid wind–PV system using a three event probability density approximation. *Solar Energy* 56 (4), 323–335.
- Bakos, G.C., Tsagas, N.F., 2003. Technoeconomic assessment of a hybrid solar/wind installation for electrical energy saving. *Energy Build* 35 (2), 139–145.
- Beaudin, M., Zareipour, H., Schellenberglobe, A., Rosehart, W., 2010. Energy storage for mitigating the variability of renewable electricity sources: an updated review. *Energy for Sustainable Development* 14, 302–314.
- Beyer, H.G., Langer, C., 1996. A method for the identification of configurations of PV/wind hybrid systems for the reliable supply of small loads. *Solar Energy* 57 (5), 381–389.
- Borowy, B.S., Salameh, Z.M., 1994. Optimum photovoltaic array size for a hybrid wind–PV system. *IEEE Transactions on Energy Conversion* 9 (3), 482–488.
- 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, 367–373.
- Castillo-Cagigal, M., Caamaño-Martín, E., Matallanas, E., Masa-Bote, D., Gutiérrez, A., Monasterio-Huelin, F., Jiménez-Leube, J., 2011a. PV self-consumption optimization with storage and active DSM for the residential sector. *Solar Energy* 85, 2338–2348.
- Castillo-Cagigal, M., Gutiérrez, A., Monasterio-Huelin, F., Caamaño-Martín, E., Masa, D., Jiménez-Leube, J., 2011b. A semi-distributed electric demand-side management system with PV generation for self-consumption enhancement. *Energy Conversion and Management* 52, 2659–2666.
- 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 Management* 43 (18), 2453–2468.
- Celik, A.N., 2003. Techno-economic analysis of autonomous PV-wind hybrid energy systems using different sizing methods. *Energy Conversion and Management* 44, 1951–1968.
- Colmenar-Santos, A., Campiñez-Romero, S., Pérez-Molina, C., Castro-Gil, M., 2012. Profitability analysis of grid-connected photovoltaic facilities for household electricity self-sufficiency. *Energy Policy* 51, 749–764.
- Diaf, S., Diaf, D., Belhamel, M., Haddadi, M., Louche, A., 2007. A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy* 35 (11), 5708–5718.
- Diaf, S., Belhamel, M., Haddadi, M., Louche, A., 2008. Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica Island. *Energy Policy* 36 (2), 743–754.
- Eke, R., Kara, O., Ulgen, K., 2005. Optimization of a wind/PV hybrid power generation system. *International Journal of Green Energy* 2 (1), 57–63.
- Ekren, O., Ekren, B.Y., Ozerdem, B., 2009. Break-even analysis and size optimization of a PV/wind hybrid energy conversion system with battery storage – a case study. *Applied Energy* 86, 1043–1054.
- Hemdan, N.G.A., Kurrat, M., 2011. Interconnection of decentralized renewable resources into distribution grids: implications and planning aspects. *Electric Power Systems Research* 81, 1410–1423.
- Hocaoglu, F.O., Gerek, O.N., Kurban, M., 2009. A novel hybrid (wind–photovoltaic) system sizing procedure. *Solar Energy* 83, 2019–2028.
- Kaabeche, A., Belhamel, M., Ibtouen, R., 2011. Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system. *Energy* 36, 1214–1222.
- Kaundinya, D.P., Balachandra, P., Ravindranath, N.H., 2009. Grid-connected versus stand-alone energy systems for decentralized power – a review of literature. *Renewable and Sustainable Energy Reviews* 13, 2041–2050.
- Kellogg, W., Nehrir, M.H., Venkataramanan, G., Gerez, V., 1996. Optimal unit sizing for a hybrid wind/photovoltaic generating system. *Electric Power Systems Research* 39 (1), 35–38.
- Kim, S.K., Jeon, J.H., Cho, C.H., Ahn, J.B., Bodgan, S.H., 2008. Dynamic modeling and control of a grid-connected hybrid generation system with versatile power transfer. *IEEE Transactions on Industrial Electronics* 55 (4), 1677–1688.
- Luna-Rubio, R., Trejo-Perea, M., Vargas-Vázquez, D., Ríos-Moreno, G.J., 2012. Optimal sizing of renewable hybrids energy systems: a review of methodologies. *Solar Energy* 86, 1077–1088.
- Markvart, T., 1996. Sizing of hybrid PV-wind energy systems. *Solar Energy* 57 (4), 277–281.
- Morgan, T.R., Marshall, R.H., Brinkworth, B.J., 1997. ARES – a refined simulation programme for the sizing and optimization of autonomous hybrid energy systems. *Solar Energy* 59 (4), 205–215.
- Mulder, G., Ridder, F., Six, D., 2010. Electricity storage for grid-connected household dwellings with PV panel. *Solar Energy* 84, 1284–1293.
- Muselli, M., Nottton, G., Louche, A., 1999. Design of hybrid-PV power generator, with optimization of energy management. *Solar Energy* 65 (3), 143–157.
- Nykamp, S., Molderink, A., Hurink, J.L., Smit, G.J.M., 2012. Statistics for PV, wind and biomass generators and their impact on distribution grid planning. *Energy* 45, 924–932.
- Pecas Lopes, J.A., Hatzigiorgiou, N., Mutale, J., Djapic, P., Jenkins, N., 2007. Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities. *Electric Power Systems Research* 77, 1189–1203.
- Prasad, A.R., Natarajan, E., 2006. Optimization of integrated photovoltaic–wind power generation systems with battery storage. *Energy* 31, 1943–1954.
- Protogeropoulos, C., Brinkworth, B.J., Marshall, R., 1997. Sizing and techno-economic optimization for hybrid solar PV wind power systems with battery storage. *International Journal of Energy Research* 21, 465–479.
- Red Eléctrica de España, 2010. Guía de Consumo Inteligente (in Spanish). <[http://www.ree.es/operacion/pdf/Guia\\_Consumo\\_v2.pdf](http://www.ree.es/operacion/pdf/Guia_Consumo_v2.pdf)> (accessed 09.08.13).
- Seeling-Hochmuth, G.C., 1997. A combined optimization concept for the design and operation strategy of hybrid–PV energy systems. *Solar Energy* 61 (2), 77–87.
- Wagner, R., 1997. Large lead acid bat for frequency regulation, load leveling and solar power applications. *Journal of Power Sources* 67 (1–2), 163–172.
- Yang, H.X., Lu, L., Zhou, W., 2007. A novel optimization sizing model for hybrid solar–wind power generation system. *Solar Energy* 81 (1), 76–84.
- Yang, H., Zhou, W., Lu, L., Fang, Z., 2008a. Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm. *Solar Energy* 82 (4), 354–367.
- Yang, H., Zhou, W., Lou, C., 2008b. Optimal design and techno-economic analysis of a hybrid solar–wind power generation system. *Applied Energy* 86 (2), 163–169.
- 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. *Applied Energy* 87, 380–389.