DESIGN OF HYBRID-PHOTOVOLTAIC POWER GENERATOR, WITH OPTIMIZATION OF ENERGY MANAGEMENT

M. MUSELLI†, G. NOTTON and A. LOUCHE
Université de Corse-URA CNRS 2053, Centre de Recherches Energie et Systèmes, Route des Sanguinaires, F-20 000 Ajaccio, France

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Abstract—A methodology is developed for calculating the correct size of a photovoltaic (PV)-hybrid system and for optimizing its management. The power for the hybrid system comes from PV panels and an engine-generator—that is, a gasoline or diesel engine driving an electrical generator. The combined system is a stand-alone or autonomous system, in the sense that no third energy source is brought in to meet the load. Two parameters were used to characterize the role of the engine-generator: denoted SDM and SAR, they are, respectively, the battery charge threshold at which it is started up, and the storage capacity threshold at which it is stopped, both expressed as a percentage of the nominal battery storage capacity. The methodology developed is applied to designing a PV-hybrid system operating in Corsica, as a case study. Various sizing configurations were simulated, and the optimal configuration that meets the autonomy constraint (no loss of load) was determined, by minimizing of the energy cost. The influence of the battery storage capacity on the solar contribution is also studied. The smallest energy cost per kWh was obtained for a system characterized by an SDM = 30% and an SAR = 70%. A study on the effects of component lifetimes on the economics of PV-hybrid and PV stand-alone systems has shown that battery size can be reduced by a factor of two in PV-hybrid systems, as compared to PV stand-alone systems. © 1999 Elsevier Science Ltd.

1. INTRODUCTION

As opposed to the PV-only system, the PV-hybrid system—consisting of a photovoltaic system backed-up by an engine-generator set—has greater reliability for electricity production, and it often represents the best solution for electrifying remote areas (van Dijk, 1996). The engine-generator set (or simply engine-generator) reduces the PV component size, while the PV system decreases the operating time of the generator, reducing its fuel consumption, O&M, and replacement costs. This study’s primary objectives have been (i) to develop a sizing methodology for PV-hybrid systems that supply small and medium power levels to remote areas, and (ii) to study the influence of load profiles and of certain engine-generator parameters, such as their type, starting threshold, and stopping threshold. A case study of the approach developed is performed for Ajaccio, Corsica (41°55′N, 8°39′E).

A brief description of the overall sizing methodology is presented in Section 1. The paper gives

the physical, technical and economical hypothesis, in Section 2, in which the detailed sizing methodology is also explained. Section 3 examines the effect of the battery storage capacity on the solar contribution and the effect of the engine-generator’s operating strategy on the energy costs. Finally, an economic study is reported that compares the roles of the various subsystems in determining the lifetime of the total system.

2. SIZING METHODOLOGY

2.1. System configuration

The system (Fig. 1) consists of a PV array, a battery bank, a back-up generator (3000 rpm or 1500 rpm) driven by a gasoline- or diesel-engine, a charge controller, and an AC/DC converter. The engine-generator will be used only as a battery charger (this reduces its required rated power), and so its rated power is directly linked to the nominal battery capacity, $C_{\text{max}}$.

2.2. Description of the sizing method

The system must be autonomous, i.e. the load must be totally met by the system at all times. Such a constraint still permits an infinite number of possible system configurations. From solar
radiation data and from assumed daily load profiles, the system behavior can be simulated, and a system meeting the constraints can be sized. However, finding the best system must be done on the basis of an overall systems approach. First, certain physical and technical constraints are used to reduce the system parameters to a realistic domain. Then minimizing the energy cost leads to the optimal solution.

3. OPERATING AND DESIGN SIMULATIONS

3.1. Solar irradiation and load profiles

The sizing of PV-hybrid systems for Ajaccio will be based on 19 years of hourly total irradiation on a horizontal plane, collected at the site. The PV modules will be tilted, and so hourly total irradiation on tilted planes had to be computed, and this was done using the models of Hay and Davies (1980); Orgill and Hollands (1977). The resulting errors (RMBE = 1.4% and RRMSE = 7% for Hay and Davies model; RMBE = –2.41% and RRMSE = 8.81% for the Orgill and Hollands model) have been shown to be quite small (Poggi, 1995) for the site. In this way, hourly values of solar irradiation, $I_b(t)$, on the PV array were calculated for a tilt angle of 30°, and this data provided the input data of the simulations.

Two different types of load can be identified:
1. That provided by ‘conventional’ appliances available on the market that typically have a low energy efficiency and have been optimized not from an energy point of view, but rather from a quality–price point of view;
2. That provided by ‘adapted’ or ‘high efficiency’ appliances that are rather scarce on the market and have a higher price than conventional appliances.

In our study, two possible hourly DC-load profiles have been chosen to represent the load. The first, the ‘Low Consumption’ profile (Fig. 2), is based on ‘adapted’ loads. It has a mean daily energy consumption of 1.8 kWh per day and a peak...
power demand of 170 W, which occurs in spring and autumn. The second, the ‘Standard’ profile (Fig. 3), is based on the French utility data (EDF), as reported by Eliot (1982). It has a daily average load of 3.7 kWh per day and a peak power of 680 W, the latter occurring in the summer. For each profile, the consumption is represented by a sequence of powers \( P_c(t) \), each taken as constant over the simulation time-step, \( \Delta t \), which is normally taken as 1 h.

3.2. System characteristics

3.2.1. Photovoltaic subsystem. PV modules: For the PV subsystem, we assume a constant PV efficiency \( \eta_{pv} \) of 10%. The PV power production \( P_p(t) \) is then computed as the product of the PV efficiency, the hourly irradiation \( I_s(t) \) and the PV module area, as has been proposed by several works (Iskander and Scerri, 1996). The ‘peak-Watt’ (or ‘Wp’) price was used as a fixed economic parameter, as has been done by several authors (Keller and Afolter, 1995; Biermann et al., 1995). It was set equal to $US 5.8/Wp (5 ECU/Wp), in accordance with the prices of the French producer PHOTOWATT and others suppliers.

Module supports: A literature survey shows that the costs of module supports are in the range $US 0.35/Wp (0.28 ECU/Wp) to $US 1.9/Wp (1.5 ECU/Wp) (Imamura et al., 1992; Palz and Schmid, 1990). Using data collected from four PV suppliers (Wind and Sun, Eurosolare, Photowatt, Siemens), support costs per Wp versus the number of modules per frame are equal to $US 1.63/Wp (1.28 ECU/Wp). However, generally PV frames are used with four modules or more, and for these supports, the average price falls to $US 0.83/Wp (0.69 ECU/Wp).

Battery bank: The battery bank can be characterized by its nominal capacity \( C_{max} \), its (maximum) depth of discharge \( DOD \), taken in this study to be 70% (Tsuda et al., 1994), and two conversion efficiencies \( \rho_{ch} \) and \( \rho_{dch} \) respectively, for charge and discharge, which were taken to equal to 85% (Oldham France, 1992; Manninen and Lund, 1989). The cost of the battery is quite significant, because the initial investment is high and the battery has to be replaced several times during the PV system lifetime. The battery bank typically accounts for about 40% of the total system cost (Notten et al., 1996a). Costs of batteries per kilowatt-hour stored capacity are plotted in Fig. 4, for the various battery types marketed by several French suppliers. The battery cost is strongly affected by its type; in particular, whether it is the stationary type used in many PV applications or the starter type more readily available in developing countries. Frequently-encountered are costs of $US 130/kWh and $US 217/kWh (110 and 183 ECU/kWh). Thus, an average price of $US 180/kWh (150 ECU/kWh) may be used for estimating the battery cost. The battery lifetime is linked to physical parameters, such as the charge–discharge rate, temperature and maximum discharge; it is very difficult to correlate the lifetime with these parameters. Based on our own experiences, a battery lifetime equal to five years has been considered in this work.

Charge controller: Regulator costs vary widely. Not all regulators work on the same electronic principle, and they can include special options, such as lightning protection, digital displays, etc. We estimated the average price to be $US 0.65/
Wp (0.55 ECU/Wp) (Iskander and Scerri, 1996), which is close to the GTZ value (Biermann et al., 1995), and we based our model on this price.

Photovoltaic subsystem installation cost: There is considerable experience in the installation of small PV systems. In some PV-system projects in Corsica, the installation cost was 25% of the PV panel cost, and this is in agreement with some references (Illiceto et al., 1994; Paish et al., 1994; Abenavoli, 1991). Thus this percentage was used for the present study.

Photovoltaic subsystem O&M cost: Concerning the maintenance of the PV subsystem, we have considered an annual O&M equal to 2% of the PV system investment, and a PV system lifetime of 20 years (Notton et al., 1998).

3.2.2. Engine-generator subsystem. Engine-generators may be compared using many different characteristics, including fuel consumption, motor speed, continuous or periodic output, load factor, and noise level, etc. The higher the engine speed, the faster the wear of the parts and the shorter the lifetime; thus, a 3000 or 3600-rpm engine can only be used for a short time whereas a 1500 or 1800-rpm engine can be used continuously. One must also compare gasoline engines with 1500 and 3000-rpm diesel engines. In this study, just two parameters, ‘SDM’ and ‘SAR’ are used as indices of the engine-generator’s role, at least so far as the simulations are concerned. SDM and SAR are the thresholds in battery charge at which the engine-generator is switched on or off, respectively, each expressed as a fraction of the battery capacity.

Fuel consumption: A back-up generator is characterized by its efficiency $\eta_c$ and its consumption in relation to the produced electrical power as follows:

$$\eta_c = \frac{P_G}{PCI_vQ_v}$$

$$\frac{Q_v}{Q_v^0} = \gamma + \xi \frac{P_G}{P_G^0}$$

$$= \left[1 - \frac{P_G^0}{\eta_c PCI_v Q_v^0}\right] + \frac{P_G^0}{\eta_c PCI_v Q_v^0} \frac{P_G}{P_G^0}$$

where $P_G$ and $Q_v$ are the generator power (kW) and the hourly consumption (l/h), $P_G^0$ and $Q_v^0$ are respectively the rated power and the consumption at this rated power, and $PCI_v$ is the heating value of the fuel ($PCI_v$/diesel = 10.08 kWh·l⁻¹ and $PCI_v$/gasoline = 9.43 kWh·l⁻¹).

The ratio $Q_v^0/P_G^0$ is the specific consumption, defined as the fuel consumption required to produce, at nominal power, one kilowatt-hour of energy. Using a power law model for the consumption at rated power of gasoline engines we have:

$$Q_v^0 = 0.7368P_G^{0.2954}$$

and assuming a constant value of 0.3 l/kWh (Thabor, 1988; Calloway, 1986) for diesel engines, allows the determination of the reduced consumption versus reduced power:

- for diesel generators: $\frac{Q_v}{Q_v^0} = 0.22 + 0.78 \frac{P_G}{P_G^0}$

- for gasoline generators: $\frac{Q_v}{Q_v^0} = \left[1 - 0.576P_G^{0.2954}\right] + 0.576P_G^{0.2954} \frac{P_G}{P_G^0}$

As an example, $\gamma = 0.22$ and $\xi = 0.78$ for all diesel generators, and $\gamma = 0.29$ and $\xi = 0.71$ for a 2-kW gasoline engine. We note the presence of a consumption at zero load: 20% and 30% of the full load for diesel and gasoline back-up generators. These results are in agreement with recent works (Beyer et al., 1995a).

By using data collected from back-up generator manufacturers, we have computed the efficiencies for each type of generator, and summarize these results in Table 1.

Engine-generator price: The engine price depends on nominal power, the price per unit kW, tending to decrease with increasing nominal power. To represent this scale effect, a power law has been used:

$$C_G = C_0 (P_G^0)^{-a}$$

where $C_G$ is the cost per kW of engine-generator

<table>
<thead>
<tr>
<th>Minimum value (%)</th>
<th>Maximum value (%)</th>
<th>Standard deviation (%)</th>
<th>Average value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>16.5</td>
<td>30.9</td>
<td>3.4</td>
</tr>
<tr>
<td>Diesel 3000 rpm</td>
<td>29.8</td>
<td>44.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Diesel 1500 rpm</td>
<td>22.3</td>
<td>40.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 1. Nominal engine generator efficiencies ($\eta_c^0$)
capacity, $C_0$ the cost coefficient, and $\alpha$ the scale factor. The coefficients in this equation, obtained by fits to data provided by French suppliers, are presented in Table 2.

Components of the engine-generator: We have allowed for a fuel storage tank, at a price of $\$US 1.7/l (1.43 ECU/l), in accordance with literature from the French manufacturer GENELEC. The storage capacity is taken to be the equivalent of 20 h of continuous engine-generator operation (in fact the engine runs for only a few hours a day, on average).

The fuel price is strongly dependent on the energy policy of the country. A study (Hille and Dienhart, 1992) illustrated the diversity of fuel prices. Prices range from $\$US 0.02/l (0.016 ECU/l) to $\$US 0.75/l (0.63 ECU/l), the last figure representing that in developing countries. Transport costs can increase the fuel price by $\$US 0.12--$\$US 0.23/l (0.1 ECU--0.19 ECU/l) for each 1000 kilometers of distance the fuel must be moved by ground transport, and this is increased by a factor of nearly 40, if air transport is used. We have considered a price of $\$US 0.55/l (0.46 ECU/l) and $\$US 1.15/l (0.97 ECU/l) for diesel and gasoline fuels, respectively.

Engine generator lifetime: The engine-generator lifetime is expressed as a function of the operating hours. Table 3 summarizes the predictions available in the literature. For gasoline engines, in accordance with the great majority of authors (Sandia National Laboratories, 1990; Energelec, 1995), we have used the mean value of the range, which is an engine lifetime equals to 3500 h. For diesel engines, the 1500-rpm diesel lifetime is greater than the 3000-rpm diesel lifetime, because of the reduced rotational speed of the generator. The literature predictions (Callo-

<table>
<thead>
<tr>
<th>Type</th>
<th>$C_0$</th>
<th>$\alpha$</th>
<th>$MBE$ ($US/kW)</th>
<th>$RMSE$ ($US/kW)</th>
<th>$RMBE$ (%)</th>
<th>$RRMSE$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>718.1</td>
<td>-0.585</td>
<td>-26.3</td>
<td>180.3</td>
<td>5.4</td>
<td>23.2</td>
</tr>
<tr>
<td>Diesel 3000 rpm</td>
<td>704.1</td>
<td>-0.2626</td>
<td>-10.8</td>
<td>100.6</td>
<td>2.3</td>
<td>22.0</td>
</tr>
<tr>
<td>Diesel 1500 rpm</td>
<td>3362.2</td>
<td>-0.7184</td>
<td>-12.3</td>
<td>145.8</td>
<td>1.5</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Table 3. Statistical coefficients for the prices of back-up generators (Eq. (6))

<table>
<thead>
<tr>
<th>References</th>
<th>Type</th>
<th>Operating hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abenavoli (1991)</td>
<td>Gasoline</td>
<td>15 000</td>
</tr>
<tr>
<td>Calloway (1986)</td>
<td>Diesel</td>
<td>5000</td>
</tr>
<tr>
<td>Beyer et al. (1995a)</td>
<td>Diesel</td>
<td>30 000</td>
</tr>
<tr>
<td>Energelec (1995)</td>
<td>Diesel</td>
<td>1200</td>
</tr>
<tr>
<td>Sandia National Laboratories (1990)</td>
<td>Gasoline</td>
<td>2000 to 5000</td>
</tr>
<tr>
<td>Sandia National Laboratories (1990)</td>
<td>Diesel</td>
<td>6000</td>
</tr>
<tr>
<td>Energelec (1995)</td>
<td>Diesel 3000</td>
<td>8000</td>
</tr>
<tr>
<td>Energelec (1995)</td>
<td>Diesel 1500</td>
<td>12 000</td>
</tr>
</tbody>
</table>
an air-filter cleaning, requires 40 min of skilled labour, (14.80 $US or 12.5 ECU); (iv) that the oil filter (costing 9.10 $US or 7.7 ECU) is replaced after every two oil changes; (v) that the air-filter (10.9 $US or 9.2 ECU), and the fuel filter (5.4 $US or 4.6 ECU for gasoline and 10.9 $US or 9.2 ECU for diesel engine) and the spark plugs (4.6 $US or 3.9 ECU for gasoline engine) are changed after four oil changes. Each of these operations take 2 h (43.7 $US or 37 ECU). Accordingly, the O&M costs (in ECU/h) are to be computed from the following equations:

(i) for gasoline engines, \( C_{O&M} = \left[ (0.4005 + 0.1532P_{\text{gene}}) \times 15.2 + 120.1 \right] / 400 \)  
(ii) for 3000 rpm diesel engines, \( C_{O&M} = \left[ (0.747 + 0.1184P_{\text{gene}}) \times 15.2 + 120.8 \right] / 400 \)  
(iii) for 1500 rpm diesel engines, \( C_{O&M} = \left[ (0.242 + 0.3505P_{\text{gene}}) \times 15.2 + 120.8 \right] / 600 \)

Notton et al. (1997) have shown that the above costing hypothesis is consistent with the findings of several earlier studies.

Battery charger: The nominal power of the battery charger is related to its nominal storage capacity. One must take into account that the electrical current produced by the generator must not be greater than one fifth of the ampere-hour capacity of the battery (Sandia National Laboratories, 1990): \( P^0_{\text{charger}} = \frac{C_{\text{max}}}{5} \)  

A battery charger’s efficiency \( \eta_{\text{charger}} \) is equal to 90% according to the manufacturers MASTERVOLT and PRIMAX. For its cost, a power law relationship was used. The different parameters and the statistical errors associated are as follows: \( C_c = 1099, \alpha = -0.691, \text{MBE} = -113 \text{ $US/kW, RMSE} = 418 \text{ $US/kW, RMBE} = -0.5\% \text{ and RRMSE} = 19\% \).

3.3. Relevant dimensionless variables

Two dimensionless variables characterize the PV-hybrid system: the PV module surface and the battery storage capacity; both are independent of the daily load. For the PV area, we first define a reference area, \( S_{\text{Ref}} \) as the PV module area (m\(^2\)) that will produce, over the simulation period \( T \) (say 19 years), an electrical energy equal to the consumed energy \( L(T) \) over the same period. Thus

\[
L(T) = \sum_{t=1}^{T} P_{t}(t) \, dt = \eta_{\text{PV,Ref}} \cdot H_{\text{p}}(T) \quad (11)
\]

where \( H_{\text{p}}(T) \) is the global daily irradiation incident on PV modules inclined with an angle \( \beta \) and the summation is taken over all the days in the period \( T \). We then define the dimensionless PV area \( S_{\text{Dem}} \) as the ratio of the actual module area to the reference area \( S_{\text{Ref}} \).

We also define a dimensionless storage capacity \( C \), which is expressed in terms of days of autonomy. \( C \) is obtained by dividing the actual storage capacity by the annual mean of the daily load consumption:

\[
C = \frac{C_{\text{max}}}{L_{\text{daily}}} \quad (12)
\]

3.4. PV-hybrid system behavior. Simulation calculations

The system simulation is performed by considering a Loss of Load Probability equal to 0%; in other words, the system reliability is 100%, leading to autonomy for the system.

Given the values of irradiation on tilted planes and the consumption patterns previously described, the system behavior can be simulated using an hourly time step—several workers (Manininen and Lund, 1989; Beyer et al., 1995b) having shown that the simulation of PV systems requires only an hourly series of solar data. Based on a system energy balance and on the storage continuity equation, the simulation method used here is similar to that used by others (Sidrach de Cardona and Mora Lopez, 1992; Kaye, 1994). Considering the battery charger output power \( P_{\text{charger}}(t) \), the PV output power \( P_{\text{p}}(t) \) and the load power \( P_{\text{c}}(t) \) on the simulation step \( \Delta t \), the battery energy benefit during a charge time \( \Delta t_1 \) is given by \( (\Delta t_1 < \Delta t) \):

\[
C_1(t) = \rho_{\text{ch}} \int_{\Delta t_1} [P_{\text{p}}(t) + P_{\text{charger}}(t) - P_{\text{c}}(t)] \, dt \quad (13)
\]

The battery energy loss during a discharge time \( \Delta t_2 \) is given by \( (\Delta t_2 < \Delta t) \):

\[
C_2(t) = \left( \frac{1}{P_{\text{dch}}} \right) \int_{\Delta t_2} [P_{\text{p}}(t) + P_{\text{charger}}(t) - P_{\text{c}}(t)] \, dt \quad (14)
\]
The state of charge of the battery is defined during a simulation time-step $\Delta t$ by:

$$C(t) = C(t - \Delta t) + C_1(t) + C_2(t)$$  \hspace{1cm} (15)

If $C(t)$ reaches SAR by an energy benefit $C_1(t)$ during the charge period with the engine-generator working, the generator has to be stopped and the charge time $\Delta t_1$ during $\Delta t$ is calculated assuming a linear relation:

$$\frac{\Delta t_1}{\Delta t} = \frac{SAR - C(t - \Delta t)}{C_1(t)}$$  \hspace{1cm} (16)

Moreover, if during the discharge period when the engine generator is stopped, $C(t)$ reaches SDM, the motor is started and the discharge time $\Delta t_2$ during $\Delta t$ is calculated by a linear relation as:

$$\frac{\Delta t_2}{\Delta t} = \frac{C(t - \Delta t) - SDM}{C_2(t)}$$  \hspace{1cm} (17)

As an input of a simulation time-step $\Delta t$ (taken as 1 h), several variables must be determined: PV output power, load power, battery state of charge, and back-up generator state (ON or OFF) in the previous time-step. A battery energy balance indicates the operating strategy of the PV-hybrid system: charge (energy balance positive) or discharge (energy balance negative). Some tests are necessary to study the SOC variations as compared to the starting and stopping thresholds. If SOC$(t)$ falls below SDM, the motor is started; and if SOC$(t)$ exceeds SAR, it is stopped. So, the charge and discharge times (Eqs. (16) and (17)) must be calculated on the simulation time-step in order to compute the different energy flows in the system (Eqs. (13) and (14)). Then, the battery SOC is compared with the intrinsic parameters (maximum and minimum capacities). If SOC$(t)<C_{\text{min}}$, the system is failing and if SOC$(t)>C_{\text{max}}$, the system produces wasted energy.

By simulating many PV-hybrid systems having the same load, one can, in principle, find an infinite set of physical solutions, each solution being characterized by a PV module area $S_{\text{Dim}}$, a storage capacity $C_{\text{max}}$, and a nominal engine-generator power. Each solution defines a ‘pair’ $(S_{\text{Dim}}, C_{\text{max}})$. Several technical constraints, for example, the available products, reduces the infinite number of solutions to a finite number of configurations. For each configuration, some physical variables are calculated by simulations: the wasted energy, the working time and the fuel consumption of the engine-generator, and the times when certain subsystems need replacement. The energy cost is then computed for each pair, and the minimization of this parameter yields the optimal operating configuration.

**4. SIMULATION RESULTS**

4.1. Operating mode

To illustrate the battery energy state evolution as a function of the engine-generator thresholds, we have plotted in Figs. 5 and 6, which show, respectively, the energy stored and the engine-generator operating hours as a function of time, over five days. Assumed parameter settings for the figures are as follows: $C$=two days, the initial charge on the battery $=100\%$ of capacity, dimensionless PV module surface $=0.94$, SDM $=30\%$ and SAR $=50\%, 70\%$ and $100\%$. Also, the ‘Low

![Fig. 5. Evolution of the battery state of charge for several assumed values of the thresholds (SDM, SAR) governing the operation of the engine-generator.](image-url)
consumption’ load profile was used, and a gasoline engine was assumed.

4.2. PV-hybrid system sizing curves

Fig. 7 presents the solar contribution (defined as the percentage that the PV production is of the total energy production) versus dimensionless storage capacities (one to six days). These plots have been parameterized using dimensionless PV areas ranging from 0.81 to 1.44. We concluded that it was not necessary to consider a PV-hybrid system with a storage capacity greater than two or three days of autonomy. Sidrach de Cardona and Mora Lopez (1992) have obtained the same conclusion considering a PV-hybrid system in which the back-up generator was applied directly to the load and to a battery charger, at the same time. The simulations demonstrate that for a system with only one day of autonomy, the nominal engine-generator power is undersized and the autonomy constraint is not respected. Thus, in the remainder of this paper, only batteries with capacities greater than to two days will be considered.

Fig. 8 presents the sizing curve, as obtained assuming the Standard load profile, the SDM and SAR are equal to 30% and 80%, respectively, and a gasoline-driven engine. The existence of some ‘discontinuities’ in Fig. 8 are due to the number of changes of the engine-generator with the decrease in dimensionless PV areas. The optimal configuration, i.e., the one corresponding to the lowest energy cost, is determined for each sizing curve. In Figs. 9 and 10 (which apply to ‘Low Consumption’ and ‘Standard’ profiles respectively), we have plotted the sizing curves parameterized by the storage capacities (two to six days) for SDM = 30% and SAR = 80%.
The lowest points on the curve define the optimal configuration. Although the locations of the lowest points are indistinct around the optimal point, the optimal configuration is always obtained when the storage capacity equals two days of autonomy. These findings have been confirmed for other values of the starting and stopping thresholds.

To make these results more general, a sensitivity analysis of the energy costs to various parameters must be performed. A short sensitivity study presented in a previous paper (Notton et al., 1998) confirmed the main conclusions shown here. In previous works in our laboratory Notton et al. (1996b) applied such an optimization to a hybrid-system, but without including the engine-generator behavior in the system simulation. In that work, the stand-alone PV system without the engine-generator had been sized for several loss-of-load probabilities, and then the energy deficit was supplied by the engine-generator. This configuration has led to identical optimal contributions (75% solar and 25% fossil), whichever the engine type. In this study, the results have been found to depend on the engine type. The variations in the contributions for the diesel 1500-rpm type can be linked to its longer lifetime, which leads to reduced replacement costs. The results are very dependent on the lifetime and maintenance of the engine, and have been calculated by optimizing these two parameters (Notton et al., 1997).

4.3. Influence of the back-up generator operating strategy

In accordance with the above results, a storage capacity of two days will be used for the analysis of the back-up generator operating strategy. Also, the energy cost has been calculated for various combinations of SDM and SAR, by varying them by steps of 10% (i.e., SDM∈[30%; 90%] and SAR∈[40%; 100%]). For each combination, we computed the optimal pair leading to the lowest energy cost. Fig. 11 presents the results for each engine type and for both load profiles. The optimal configuration is obtained when SDM = 30% and SAR = 70%, regardless of the load profile and the engine-generator type.

Thus we have now demonstrated that the optimal size of the battery capacity is two days and the best energy management is obtained when SDM and SAR are respectively equal to 30% and 70% of the nominal storage capacity. The optimal PV area for each configuration is close to unity ($S_{\text{dim}} = 0.97, 0.95$ and $0.73$ for the three cases in Fig. 11). The optimal size of the engine generator is easily deduced from the optimal capacity (two days) and from Eq. (10), by dividing the battery charger rated power by the charger efficiency $\eta_{\text{charger}}$.

For the combinations of SDM and SAR and for the optimal pairs ($S_{\text{dim}}, C_{\text{max}}$) of Fig. 11, we have combined the solar contribution curves obtained for a battery capacity of two days to deduce optimal solar and fossil fuel contributions for each engine-generator type, and these are given in Table 4.

In previous works in our laboratory Notton et al. (1996b) applied such an optimization to a hybrid-system, but without including the engine-generator behavior in the system simulation.
Fig. 9. Sizing curves obtained for a storage capacity ranging from 2 to 6 days of autonomy, for each engine type (The Low Consumption load profile is assumed).
Fig. 10. Sizing curves obtained for storage capacities ranging from 2 to 6 days of autonomy, for each engine type (Standard load profile is assumed.)
Fig. 11. Influence of back-up generator operating strategy according to engine type.
Table 4. Optimal contributions for each back-up generator type

<table>
<thead>
<tr>
<th>Motor type</th>
<th>Load profiles</th>
<th>Optimal contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>Low consumption/standard</td>
<td>75</td>
</tr>
<tr>
<td>Diesel 3000 rpm</td>
<td>Low consumption/standard</td>
<td>80</td>
</tr>
<tr>
<td>Diesel 1500 rpm</td>
<td>Low consumption/standard</td>
<td>65</td>
</tr>
</tbody>
</table>

operating strategy on the wasted energy $WE(T)$ produced by the system,

$$WE(T) = \sum_{P_p(t) > P_e(t)} \frac{[P_p(t) - P_e(t)] dt}{C(t) / C_{\text{max}}}$$

For example, for a gasoline engine the influence of the stopping threshold ($\text{SAR} \in [40\%; 70\%]$) on the wasted energy for a given starting threshold ($\text{SDM} = 30\%$) is shown in Fig. 12. We found a trivial result: increasing the PV module increases the energy excess. On the other hand, the charge strategy represented by the SAR variation is not significant. The increase of SAR causes an increase from 2 to 4% of the energy surplus over all PV area ranges. We note that, considering the optimal configurations previously given ($S_{\text{Dim}} = 0.97$ for gasoline engine), the energy surplus is inferior to 5%; this demonstrates the competitiveness of hybrid-PV systems, as compared to stand-alone PV/battery systems with an energy excess about 50%.

4.5. Economical study on the PV-hybrid system lifetime

From optimal configurations previously described ($\text{SDM} = 30\%$ and $\text{SAR} = 70\%$), for each engine type and for the Low Consumption load profile, we have determined the investment, maintenance and replacement costs for each subsystem during its lifetime. The results are presented in Fig. 13. For hybrid systems using gasoline and 3000-rpm diesel engine-generators, the PV contribute 35% and the engine contributes 40% of the total cost. The total investment cost is made up of the following: PV modules about 30%, engine-generator about 20%, PV support about 4%, O&M for the engine-generator about 5%, and the charge controller about 3.5%. With the lifetime of a gasoline engine being lower than the lifetime of a 3000-rpm diesel engine, the gasoline engine must be replaced during the hybrid-system lifetime, whereas the diesel engine does not. Moreover, the fuel consumption cost is greater for the gasoline engine, because its fuel consumption and its fuel prices are higher than those for a 3000-rpm diesel engine. For the system using the 1500-rpm diesel engine, the initial costs are more important: the PV and engine-generator investment (about 20% and 50%), PV support parts (about 3%), the O&M back-up generator (about 3%), and the charge controller investment (about 3%). We note that the battery contribution to the cost is about 20% (made up of about 9% for investment and 11% for replacement) regardless of the engine type. This result agrees with previous findings (Notton et al., 1996a) relating to stand-alone PV/battery systems, for which the storage represents 40% on the total lifetime cost. Thus the addition of a back-up generator to a traditional PV system cuts the
battery’s contribution to the total cost by a factor of two. Previously, Notton et al., 1996b showed that the energy cost produced by a PV hybrid system is half of a traditional PV/battery stand-alone system.

5. CONCLUSIONS

In this paper, we have studied the behavior of a stand-alone PV-hybrid (PV and engine-generator) system. We have considered the sizing of PV systems by using hourly total irradiation values on tilted surfaces and hourly load profiles taken as constant over the seasons. The study has shown that the optimal configuration, i.e., the configuration that minimizes the energy cost, is obtained with a battery storage capacity of two days. The influence of the engine-generator’s operating strategy has also been studied. It was found that an optimal configuration is one where the engine-generator is switched on when the battery charge is at 30% of maximum battery capacity and where it is turned off when the battery charge is 70% of maximum battery capacity. The study has determined optimal contributions for both solar and fossil fuel energy sources. For gasoline powered engine-generators, the combination of 75% SOLAR with 25% FOSSIL are the most economical solutions, and 3000-rpm diesel powered engine-generators, 80% SOLAR and 20% FOSSIL are the most economical solutions. For 1500-rpm diesel powered engine-generators, the optimal combination is 65% SOLAR with 35% FOSSIL, the contribution of fossil in the latter combination being higher, because of the longer lifetime of a diesel engine. The work has demonstrated the competitiveness of PV-hybrid systems, which can work with an energy excess as low as 5% and a battery storage half of that of the traditional stand-alone PV system, based on the system lifetime. In conclusion, the approach presented here appears to be a valuable tool for the design and evaluation of PV-hybrid systems supplying power in remote areas.

NOMENCLATURE

- $C$: Dimensionless battery storage capacity
- $C(t)$: Battery state of charge
- $C_i(t)$: Battery energy benefit during the period $\Delta t$
- $C_2(t)$: Battery energy loss during the period $\Delta t$
- $C_0$: Cost coefficient
- $C_G$: kW price
- $C_{\text{max}}$: Nominal storage capacity
- $C_{\text{min}}$: Minimal storage capacity
- $D$: Depth of discharge
- $DOD$: Depth of discharge
- $H_o(T)$: Solar irradiation received by PV modules on a tilted plane
- $I_o(T)$: Hourly solar irradiation on tilted plane
- $L_i(T)$: Energy consumed by load in the period $T$
- $P(i)$: Instantaneous power to the load
- $PCLI$: Heating value of fuel
- $P_G$: Generator power
- $P_i$: Instantaneous power representing the load
Design of hybrid photovoltaic power generator, with optimization of energy management

References


