PERGAMON

Renewable Energy 20 (2000) 1–7

RENEWABLE ENERGY

www.elsevier.com/locate/renene

PV-hybrid power systems sizing incorporating battery storage: an analysis via simulation calculations

M. Muselli*, G. Notton, P. Poggi, A. Louche

Université de Corse — URA CNRS 2053, Centre de Recherches Energie et Systèmes, Route des Sanguinaires, F-20 000, Ajaccio, France

Received 17 May 1999; accepted 21 June 1999

Abstract

A methodology is developed to determinate the optimal size of PV-hybrid subsystems and to optimize the stand-alone system management. Two particular parameters characterize the back-up engine generator: SDM and SAR, respectively the starting and the stopping thresholds calculated as a part of the nominal storage capacity. Using simulation calculations, the optimal configuration leading to the autonomy constraint, is determined on the basis of a minimization of the kWh cost. The operating back-up generator strategy study has shown that the smallest kWh cost is obtained for a system characterized by a SDM = 30% and SAR = 70% of the nominal battery capacity.

Keywords: Hybrid power systems; Off grid systems; Design method; PV back-up generator systems; Life-cycle costing

1. Introduction

A PV-hybrid system, combination of a photovoltaic system with a back-up generator, allows to obtain a great reliability of the electricity production and is

* Corresponding author. Tel.: + 33-4-95-52-41-41; fax: + 33-4-95-52-41-42.
E-mail address: muselli@vignola.univ-corse.fr (M. Muselli)

0960-1481/00/$ - see front matter
PII: S0960-1481(99)00094-4

often the best solution to electrify remote areas. The main objective of this paper is to study the design and the operation of PV-hybrid systems to supply small power loads located in remote areas by introducing in the simulation the impact of the starting (SDM) and the stopping (SAR) thresholds of the engine generator calculated from the nominal storage capacity. After the presentation of physical and economical hypothesis used to compute the life cycle cost, we present the algorithm on a simulation time-step. At last, this model is applied to determine the PV-hybrid system configuration leading to the lower kilowatt-hour cost.

2. Sizing methodology — physical and economical hypothesis

The system is composed of a PV array, a battery bank, a gasoline or diesel back-up generator (3000 or 1500 rpm), a charge controller and an AC/DC converter (Fig. 1). In this study, the motor is used as a battery charger and its power is directly linked to the nominal battery capacity.

From hourly solar radiation data and from hourly load profiles [1], the simulation model is similar to various methodologies [2,3] based on a system energy balance and on the storage continuity equations. This system must be autonomous (LOLP = 0%) (at every moment the load must be only supplied by this system). Such a constraint leads to an infinity of possible system configurations. Other technical constraints allow to reduce this system characteristics set to a more physical domain. At last, the use of the kilowatt-hour cost produced by the system and its minimization constraint, lead to the most optimized system. Physical (efficiencies) and economical (investment cost, lifetime) hypothesis are resumed in Table 1.

Concerning the engine generator and the battery charger price, a power law, based on the nominal power (P_{nom}) of each subsystem, is used (C_{G} is the kW price, C_0 the cost coefficient and α the scale factor):

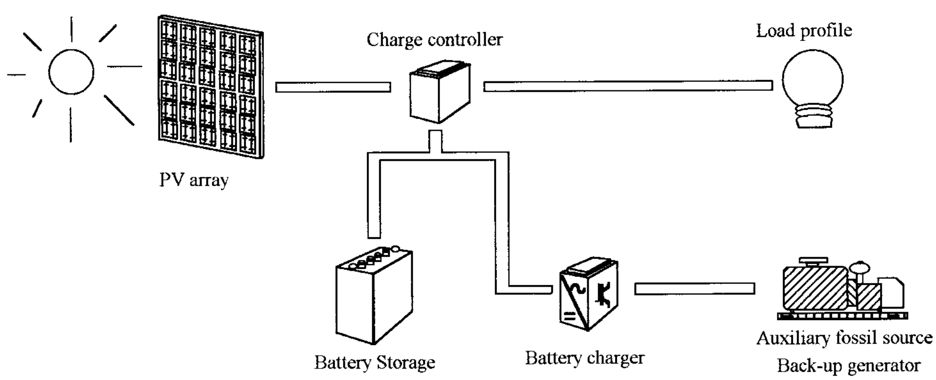

Fig. 1. Circuit diagram showing the connections between the various components.

Table 1
Hypothesis used in this work

Subsystem	Efficiencies	Cost (ECU)	Installation cost	Lifetime	O and M costs
PV modules	10%	5000/kW	25%	20 years	2% of the investment cost
PV supports		690/kW	25%	20 years	2% of the investment cost
Battery storage	$\eta_{charge}=85\%$ $\eta_{discharge}=85\%$ DOD = 70%	150/kWh	25%	5 years	2% of the investment cost
Controller	100%	550/kW	25%	10 years	2% of the investment cost
Gasoline engine	21.1%	$C_0=760$ $\alpha=-0.59$	10%	3500 h	$[(0.4+0.2.P_G)\times 15.2+120.1]/400$
Diesel 3000 rpm	35.3%	$C_0=649$ $\alpha=-0.26$	10%	6000 h	$[(0.7+0.1.P_G)\times 15.2+120.8]/400$
Diesel 1500 rpm	29.9%	$C_0=3103$ $\alpha=-0.72$	10%	10,000 h	$[(0.2+0.4.P_G)\times 15.2+120.8]/600$
Battery charger	90%	$C_0=1099$ $\alpha=-0.69$		20 years	

$$C_G(\mathrm{ECU/kW}) = C_0 P_{\mathrm{nom}}^{\alpha}. \tag{1}$$

To estimate the kWh cost, several regressions presented in a previous study [4] allow to compute the maintenance of the back-up generator by using its nominal power P_G (Table 1, in ECU by operating h) and the replacement costs of each subsystem. The simulations are computed using 19 years of hourly global solar irradiations on tilted planes (30°) on the site of Ajaccio (41° 55′ N, 8° 44′ E) located in Corsica island. Two seasonal hourly DC load profiles have been chosen to simulate user consumptions (Fig. 2): 'Low Consumption' profile (1.8 kWh/day) constructed with 'adapted' loads [5] and 'Standard' profile (3.7 kWh/day) based on the French utility EDF data [6].

Considering the battery charger output power $P_{\mathrm{charger}}(t)$, the PV output power $P_{\mathrm{p}}(t)$ and the load power $P_{\mathrm{c}}(t)$ on the time-step Δt, the battery energy benefit $C_1(t)$ during a charge time Δt_1 and the battery energy loss $C_2(t)$ during a discharge time Δt_2 are given by:

$$C_1(t) = \eta_{\mathrm{charge}} \int_{\Delta t_1} [P_{\mathrm{p}}(t) + P_{\mathrm{charger}}(t) - P_{\mathrm{c}}(t)]\mathrm{d}t \tag{2}$$

$$C_2(t) = \left(\frac{1}{\eta_{\mathrm{discharge}}}\right) \int_{\Delta t_2} [P_{\mathrm{p}}(t) + P_{\mathrm{charger}}(t) - P_{\mathrm{c}}(t)]\mathrm{d}t \tag{3}$$

If during the charge period with the engine generator working, $C(t)$ reaches SAR by an energy benefit $C_1(t)$, the generator has to be stopped and the charge time

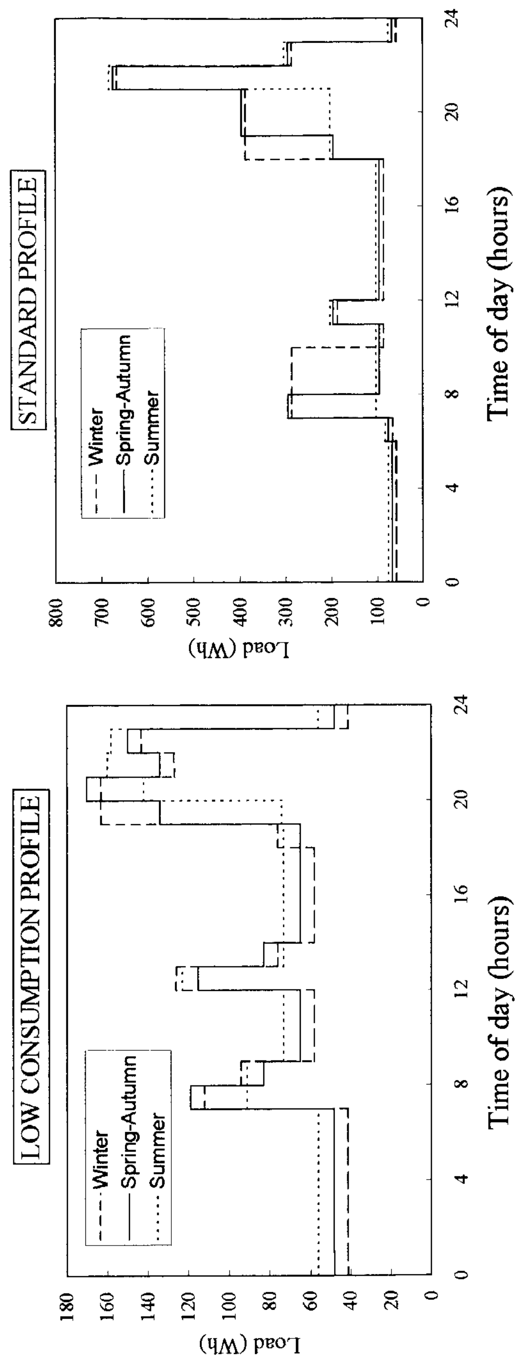

Fig. 2. Hourly load profiles.

Δt_1 during Δt is calculated considering a linear regression as:

$$\frac{\Delta t_1}{\Delta t} = \left| \frac{\mathrm{SAR} - C(t - \Delta t)}{C_1(t)} \right| \tag{4}$$

Moreover, if during the discharge period with the engine generator stopped, $C(t)$ reaches SDM, the motor is started and the discharge time Δt_2 during Δt is calculated considering a linear regression as:

$$\frac{\Delta t_2}{\Delta t} = \left| \frac{C(t - \Delta t) - \mathrm{SDM}}{C_2(t)} \right| \tag{5}$$

As an input of a simulation time-step, several variables must be determined: PV output power, load power, battery state of charge and back-up generator state (ON/OFF). 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 $\mathrm{SOC}(t)$ falls down under SDM, the motor is started and if $\mathrm{SOC}(t)$ exceeds SAR, it is stopped. So, the charge and discharge times must be calculated on the time-step allowing to compute the different energy flux in the system. Then, the battery SOC is compared with accumulators intrinsic parameters: if $\mathrm{SOC}(t) < C_{\mathrm{min}}$ (minimum storage capacity) the system is failing and if $\mathrm{SOC}(t) > C_{\mathrm{max}}$ (maximum storage capacity), the system produces wasted energy.

3. Results and discussion

We have studied the influence of the storage capacity on the solar contribution

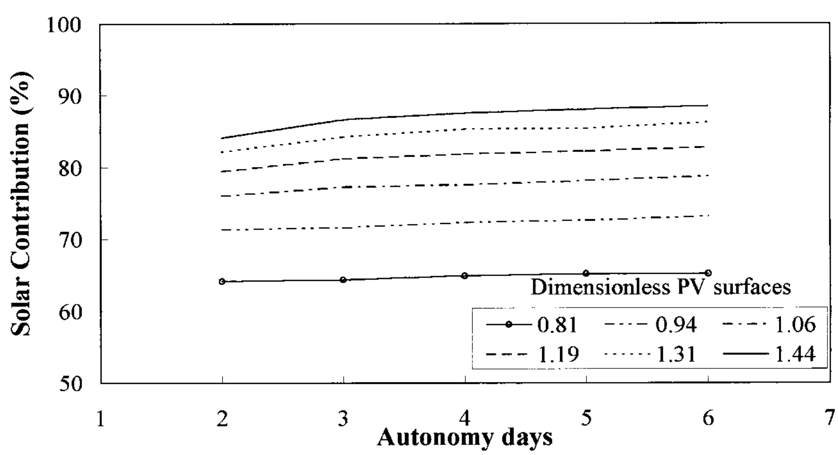

Fig. 3. Solar contribution versus days of autonomy.

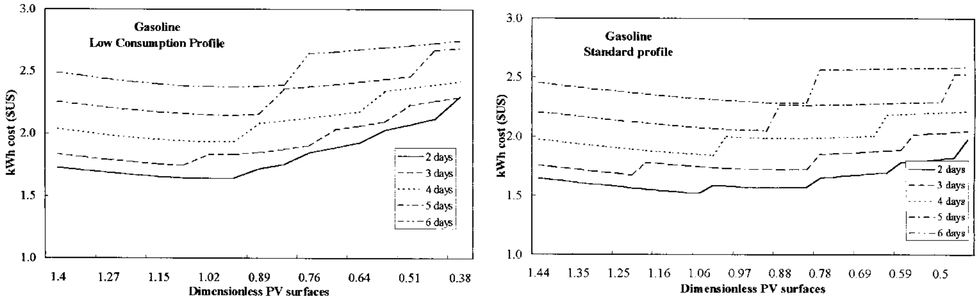

Fig. 4. Sizing curves for both load profiles.

for several dimensionless PV module areas in order to limit the influence of the load profile (Fig. 3). The conclusion is that it is not necessary to consider a PV-hybrid system with a storage capacity higher than 2 or 3 days of autonomy (with one day, the engine nominal power is undersized and we noted the loss of the autonomy constraint).

Then, the different sizing curves have been calculated for each load profile and for storage capacities varying between 2 to 6 days (Fig. 4). The optimal configurations allowing to obtain the minimal kWh cost, are always defined by a storage capacity equal to 2 days of autonomy.

Moreover, the influence of the back-up generator strategy has been studied by computing for each couple the optimal configuration (SDM $\in$ [30% of $C_{\max}$, 90%

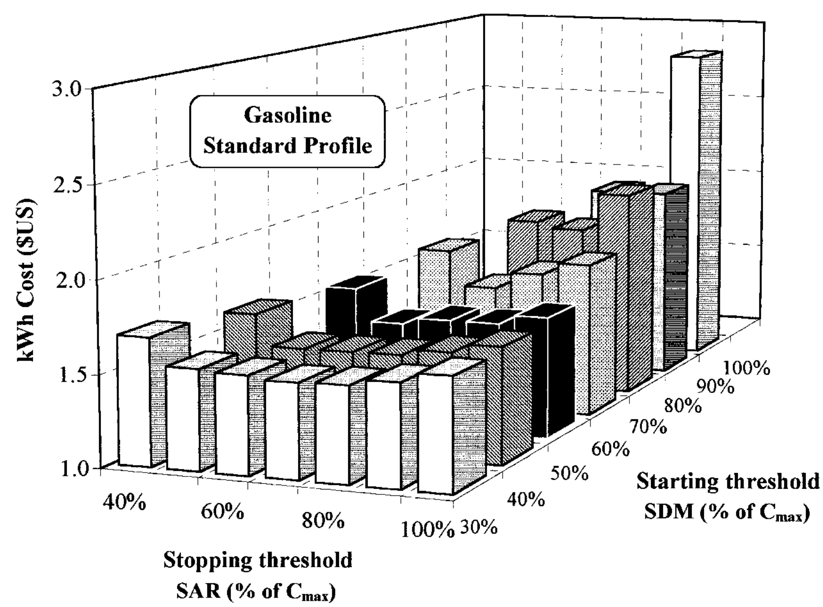

Fig. 5. Influence of the motor strategy.

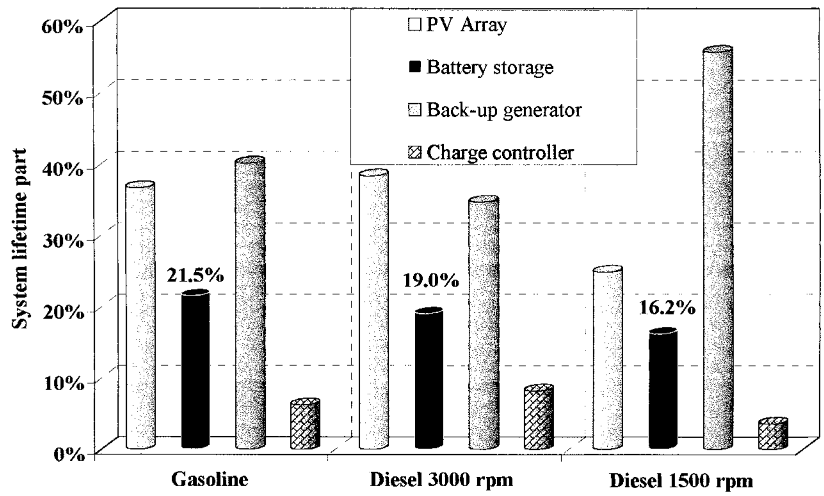

Fig. 6. Economic analysis on the system lifetime.

of $C_{\max}$], SAR $\in$ [40% of $C_{\max}$, 100% of $C_{\max}$] by steps of 10%) (Fig. 5). Whatever are the load profile and the engine generator type, the optimal operating strategy is defined by a starting and a stopping thresholds equal to respectively 30 and 70% of $C_{\max}$.

By coupling these previous results, optimal solar and fossil contributions have been deduced: 75% solar and 25% fossil for gasoline motor, 80/20 and 65/35% for diesel 3000 and 1500 rpm generators. At last, an economical study (Fig. 6) on the PV-hybrid system lifetime in optimal configurations presented previously, has shown that the storage part (investment, maintenance and replacement costs) is reduced by a factor of 2 as compared to traditional stand-alone PV system [4].

In conclusion, the presented approach is a valuable tool to design and evaluate PV-hybrid power supply systems for remote areas in terms of sizing and system operation.

References

[1] Beyer HG, Bolhen M, Schumacher J. GENG. A solar modelisation data generation for the simulation system INSES. In: Proceedings of the 13th European Photovoltaic Solar Energy Conference, Nice, 1995. p. 982–5.

[2] Ramakumar R, Abouzahr I, Ashenayi K. A knowledge-based approach to the design of integrated renewable energy system. IEEE Transactions on Energy Conversion 1992;7(4):648–59.

[3] Egido M, Lorenzo E. The sizing of stand-alone PV systems: a review and a proposed new method. Solar Energy Materials and Solar Cells 1992;26:51–69.

[4] Notton G, Muselli M, Poggi P. Costing of a stand-alone PV system. Energy 1998;23:289–308.

[5] Muselli M. Electrification de sites isolés. Dimensionnement de systèmes Hybrides à Sources Renouvelables d'Energies. PhD thesis, University of Corsica, 1997.

[6] Eliot P. Analyses d'un habitat PV en site isolé. PhD thesis, University of Nice, 1982.