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Solar Energy 76 (2004) 295–299

SOLAR ENERGY

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Economic evaluation and optimization of hybrid diesel/photovoltaic systems integrated to utility grids

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Received 17 February 2003; received in revised form 6 August 2003; accepted 7 August 2003

Abstract

An analytical approach to evaluate and to optimize the life cycle savings of hybrid diesel-photovoltaic plants is carried out. The life cycle savings is evaluated, considering one or more diesel generator sets, operating in different fixed power levels, with special attention to the case of high specific fuel cost. The condition under which optimum photovoltaic module area exists is analyzed. In the particular region of the northern part of Brazil, it is shown that there are several favorable conditions to implement photovoltaic generation, in the range of current electricity tariffs and diesel oil costs practiced in the market.

1. Introduction

In remote villages far from the utility grids of many countries, electric energy is usually supplied by diesel generators or by small hydroelectric plants. It is the case of most of the villages in the northern and northeast part of Brazil, where around 500 MWe are supplied by private companies and distributed to the customers through local grids. In spite of the fact the diesel fuel is subsidized, the transportation cost for the most part of the cases becomes so expensive that the hybrid diesel-photovoltaic generation becomes competitive with diesel-only generation. In many circumstances the diesel generation is the only solution for energy supply in short terms, as is the case of high electric energy deficit. However, diesel-only generation cannot be considered as a solution for large scale supply distributed energy to the grid, because of CO_2 emissions, the price inflation of the fuel, and the increasing penalty cost due to environmental protection policies adopted by many countries (Schramm, 2000; Cabraal et al., 1998). On the other hand, diesel can be saved if photovoltaic plants are installed, in combination with diesel generation plants, either integrated to the public grid or to isolated grids (Bazzo et al., 2000).

A large number of parameters have to be considered in the economical analysis and optimization of hybrid diesel-photovoltaic generation plants. In addition to the specific cost function of the *electrical diesel generator* (EDG), it should be considered the operating power fraction for every month, the monthly energy expected demand or the monthly amount of energy to be replaced by photovoltaics in order to save the fuel, and the electric energy cost and its revenue value, as well as the capital cost. This quite large number of parameters and its effect on the life cycle savings of the plant would be difficult to handle by empirical direct calculations. Therefore, an analytical approach is convenient in order to develop a general analytical tool for straightforward evaluation and optimization.

In the present paper, it is assumed that the photovoltaic plant is integrated to the grid, in combination with three or more EDG (one is a backup engine), and no battery is utilized. Furthermore, operation and maintenance costs as well as the capital cost of the EDG are not considered. The costs considered here are the

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doi:10.1016/j.solener.2003.08.008

Nomenclature

EDG	electrical diesel generator (diesel generator set)
$\dot{E}_{\mathrm{N}}$	nominal power [kW]
$\dot{E}_{\mathrm{OP}}$	stationary operating power [kW]
$\Delta t_{\mathrm{e}i}$	operating time interval, second [s]
E_{N}	amount of the energy generated in the time interval $\Delta t_{\mathrm{e}i}$, at the nominal power [J]
S_i	amount of energy supplied by PV to the grid [J]
$\overline{H}_{\mathrm{T}i}$	monthly average daily total solar radiation incident on the tilted surface [J/m^2]
N_i	number the days of the month
A_{c}	PV panel area [m^2]
Δt_i	maximum sunshine hours of the month (i) [s]
n_i	number of hours of time interval centered at the solar noon
ΔE_i	amount of energy demand increase in the month (i)
$E_{\mathrm{N}i}$	energy produced in the month (i) corresponding to the nominal engine power
P_1	ratio of life cycle fuel savings to first year fuel energy cost, dimensionless
P_2	ratio of owning cost to initial cost, dimensionless
C_{E1}	cost of electric energy in the first year of the period of economical analysis, US\$ kW h^{-1}
C_{PV}	revenue specific value of the electric energy produced by PV, US\$ kW h^{-1}
C_{A}	cost of PV panel per unitary area, US\$ m^{-2}
C_{E}	cost independent of PV panel area, US\$

LCS	life cycle savings, US\$
C	cost constant

Greek symbols

ζ	specific energy cost of the electrical diesel generator, US\$ kW h^{-1}
φ	cost function
$\underline{\eta}_i$	monthly PV array efficiency
$\underline{\beta}_i$	ratio of the monthly average of the hourly solar radiation incident on the panel for the time interval $\Delta t_{\mathrm{e}i}$, to the average $\overline{H}_{\mathrm{T}i}$
$\Delta\lambda_{\mathrm{e}i}$	ratio of the amount of energy demand increase in the month (i), ΔE_i, to $E_{\mathrm{N}i}$
β_i	ratio of $\Delta t_{\mathrm{e}i}$ to Δt_i
$\Delta\lambda_{\mathrm{s}i}$	power shift due two the income of energy generated by PV in the month (i), dimensionless

Subscripts

CAP	capital cost of the PV array
E	cost independent of the PV panel area
E1	electric energy cost in the first year of the economical analysis
ei	operation of the electric diesel engine in the month (i)
i	ith month
N	nominal power of the electric diesel engine
op	continuous operating power fraction
PV	photovoltaic panel
si	shift of power in the month (i)
T	tilted surface

capital cost of the photovoltaic plant, the fuel cost of the EDG, the electric energy revenue value and also the photovoltaic energy revenue value.

2. Economic analysis

The specific energy cost generation of an EDG is known to be dependent on the operating power of the Diesel engine. The smaller the operating power the higher the specific energy cost. In the present analysis it is assumed that the specific energy cost of the EDG can be best fitted by a correlation given by

$$\zeta(\lambda) = \delta/\lambda + \alpha\exp(-\gamma\lambda) + \beta \tag{1}$$

where α, β, γ, and δ are constants to be determined by the minimum square error fitting, and $\lambda = \dot{E}_{\mathrm{OP}}/\dot{E}_{\mathrm{N}}$, where $\dot{E}_{\mathrm{N}}$ is the nominal power and $\dot{E}_{\mathrm{OP}}$ is the stationary operating power of the EDG. The correlation given above is suggested by experimental data obtained from continuous power operation of several EDG available in the market, as reported in the manufacturer catalog (Deutz, 2001). For a given operating time interval $\Delta t_{\mathrm{e}i}$, and a given operating power $\dot{E}_{\mathrm{OP}}$, the amount of the electrical energy produced by the EDG is given by $\dot{E}_{\mathrm{OP}}\Delta t_{\mathrm{e}i}$. The associated cost to generate this amount of energy is then given by

$$D = \zeta(\lambda)\dot{E}_{\mathrm{OP}}\Delta t_{\mathrm{e}i} \tag{2}$$

where $\dot{E}_{\mathrm{OP}} = \lambda\dot{E}_{\mathrm{N}}$. Therefore Eq. (2) can be written as

$$D = \varphi(\lambda)E_{\mathrm{N}} \tag{3}$$

where $\varphi = \lambda\zeta(\lambda)$ and $E_{\mathrm{N}} = \dot{E}_{\mathrm{N}}\Delta t_{\mathrm{e}i}$

As can be seen by inspection of Eq. (2), if $\dot{E}_{\mathrm{OP}}$ vanishes D reaches its minimum value $E_{\mathrm{N}}\delta$. The function $\varphi(\lambda)$ is a monotonically increasing function of λ, and its derivative also increases with λ. This particular behavior of φ will be shown later to be significant for the optimization of hybrid photovoltaic-diesel generation plants, in terms of the total area of the photovoltaic panels.

In the present analysis, the energy generated by the photovoltaic plant integrated to the grid is expressed as a linear function of the collector area, as assumed in Colle et al. (2001).

The efficiency of the panels are replaced by the monthly average photovoltaic plant efficiency η_i, for each month considered (Rüther and Dacoregio, 2000). The amount of expected photovoltaic energy supplied to the grid in the month (i) is assumed to be expressed by $S_i = \eta_i \overline{H}_{\mathrm{T}i} N_i A_\mathrm{c}$, where $\overline{H}_{\mathrm{T}i}$ is the average of the monthly means of solar radiation incident on the tilted panels, N_i is the number of days of the month considered and A_c is the total panel area.

Let $\Delta t_{\mathrm{e}i}$ be the time interval of operation of the EDG in the month (i), where $\Delta t_{\mathrm{e}i} \leqslant \Delta t_i$ and Δt_i is the sum of the maximum sunshine hours of the month (i). Here, $\Delta t_{\mathrm{e}i} = n_i N_i$ where n_i is the number of hours of the time interval centered at the solar noon. In this time interval, the monthly amount of the energy due to photovoltaic generation is given by $\eta_i \overline{\beta}_i \overline{H}_{\mathrm{T}i} N_i A_\mathrm{c}$, where $\overline{\beta}_i$ is the ratio of the monthly average of the hourly solar radiation incident on the panel for the time interval $\Delta t_{\mathrm{e}i}$, and the average $\overline{H}_{\mathrm{T}i}$. Let $\lambda_{\mathrm{op}i}$ be the operating power fraction of the EDG in the time interval $\Delta t_{\mathrm{e}i}$. By definition of λ, $\lambda_{\mathrm{op}i}$ can be written as follows

$$\lambda_{\mathrm{op}i} = \frac{\dot{E}_\mathrm{OP} \Delta t_{\mathrm{e}i}}{\dot{E}_\mathrm{N} \Delta t_{\mathrm{e}i}} \tag{4}$$

If ΔE_i is the amount of energy demand increase in the month (i), the EDG should increase its average operating power from $\lambda_{\mathrm{op}i}$ to $\lambda_{\mathrm{op}i} + \Delta\lambda_{\mathrm{e}i}$, where $\Delta\lambda_{\mathrm{e}i} = \Delta E_i / \dot{E}_\mathrm{N} \Delta t_{\mathrm{e}i}$. Let us define $\beta_i = \Delta t_{\mathrm{e}i} / \Delta t_i$. The net fraction of power that should be supplied by the photovoltaic plant in order to compensate the amount of energy ΔE_i is expressed by

$$\Delta\lambda_{\mathrm{s}i} = \frac{\overline{\beta}_i \eta_i \overline{H}_{\mathrm{T}i} N_i A_\mathrm{c}}{E_{\mathrm{N}i} \beta_i} - \Delta\lambda_{\mathrm{e}i} \tag{5}$$

where $\Delta\lambda_{\mathrm{s}i} \geqslant 0$, in the case the photovoltaic plant is supposed to supply at least the energy amount ΔE_i in each month (i), and $E_{\mathrm{N}i} = \dot{E}_\mathrm{N} \Delta t_i$ is the nominal energy produced in the month (i). $\overline{\beta}_i$ is numerically determined from the daily distribution of the hourly totals of global radiation on the tilted panel. The details of the calculation of $\overline{\beta}_i$ will not be presented here. The variable $\Delta\lambda_{\mathrm{s}i}$ can either be positive or negative, depending on the size of A_c.

If the EDG would have to supply at least the same energy expected to be supplied by the photovoltaic plant, from Eq. (3), the cost due to the power variation of the EDG in the month (i) is expressed by

$$D_i = f_i \dot{E}_\mathrm{N} \Delta t_{\mathrm{e}i} = f_i \beta_i E_{\mathrm{N}i} \tag{6}$$

where

$$f_i = \varphi(\lambda_{\mathrm{op}i} + \Delta\lambda_{\mathrm{e}i}) - \varphi(\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{s}i}) \tag{7}$$

and $\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{s}i} \geqslant 0$ and $\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{e}i} \leqslant 1$. Similar expressions for Eqs. (6) and (7) are developed for $\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{s}i} < 0$ and $\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{e}i} > 1$ and reported in Colle et al. (2001). In the complementary time interval $\Delta t_i - \Delta t_{\mathrm{e}i}$ of the month (i), where the EDG operates also at the power fraction $\lambda_{\mathrm{op}i}$, the energy input expected in the grid produced by the photovoltaic panels is $(1 - \overline{\beta}_i) \eta_i \overline{H}_{\mathrm{T}i} N_i A_\mathrm{c}$.

By the definition of λ, the equivalent power shift corresponding to the energy generated by the EDG is expressed by

$$\Delta\lambda_{\mathrm{o}i} = \frac{(1 - \overline{\beta}_i) \eta_i \overline{H}_{\mathrm{T}i} N_i A_\mathrm{c}}{\dot{E}_\mathrm{N} (\Delta t_i - \Delta t_{\mathrm{e}i})} \tag{8}$$

Since $\Delta t_{\mathrm{e}i} = \beta_i \Delta t_i$ and $\Delta t_i - \Delta t_{\mathrm{e}i} = (1 - \beta_i) \Delta t_i$, Eq. (8) can be expressed as

$$\Delta\lambda_{\mathrm{o}i} = \frac{(1 - \overline{\beta}_i) \eta_i \overline{H}_{\mathrm{T}i} N_i A_\mathrm{c}}{E_{\mathrm{N}i} (1 - \beta_i)} \tag{9}$$

The saving due to the reduction of the operating power of the EDG, from the fraction $\lambda_{\mathrm{op}i}$ to the fraction $\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{o}i}$ can be expressed as

$$D_i = h_i (1 - \beta_i) E_{\mathrm{N}i} \tag{10}$$

where

$$h_i = \varphi(\lambda_{\mathrm{op}i}) - \varphi(\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{o}i}) \tag{11}$$

for $\lambda_{\mathrm{op}i} - \Delta\lambda_{\mathrm{o}i} \geqslant 0$. The present analysis can easily be extended to the case of two or more EDGs and it is not presented here.

The $P_1 - P_2$ method developed in Duffie and Beckman (1991) is used here to evaluate the life cycle savings function. From Eqs. (6) and (10), the present value of the savings due to the EDG's operating power change that is required to generate the same energy input of the photovoltaic plant, can be expressed as

$$D = P_1 \sum_{i=1}^{12} g_i E_{\mathrm{N}i} \tag{12}$$

where P_1 is the present worth factor of the early savings for the time period of N_e years of the economical analysis, and g_i is given by

$$g_i = \beta_i f_i + (1 - \beta_i) h_i \tag{13}$$

In the first year of the economical analysis, the energy is sold to the grid at a specific cost $C_{\mathrm{E}1}$. It is assumed here that to the energy produced by the photovoltaic plant is assigned a revenue specific value C_PV. Revenue values up to the double of the revenue value of the electric energy are established in many countries, in order to increase the competitiveness of the photovoltaic energy integrated to the utility grid. Therefore, the income due to the photovoltaic energy input to the grid is given by

$$E_{PV} = P_1(C_{PV} - C_{E1})\sum_{i=1}^{12}\eta_i\overline{H}_{Ti}N_iA_c \tag{14}$$

Let C_A be the capital cost of the photovoltaic panel per unit area and C_E be the cost independent of the total area A_c. The present value of all the expenses related to the capital cost of the photovoltaic plant is given by

$$C_{CAP} = P_2(C_AA_c + C_E) \tag{15}$$

where P_2 accounts for the down payment of the collectors, the present value of the mortgage payment for a given interest rate, expenses due to insurance, resale value, depreciation and other minor costs. The equations for P_1 and P_2 are given in Duffie and Beckman (1991). In the present analysis it is assumed that the down payment is equal to the total cost of the photovoltaic plant, so that P_2 is made equal to the unity.

The life cycle savings LCS is defined as

$$\mathrm{LCS} = D + E_{PV} - C_{CAP} \tag{16}$$

Replacing D, E_{PV} and C_{CAP} by their definitions given by Eqs. (12), (14) and (15) in Eq. (16), it leads to

$$\mathrm{LCS} = g(A_c) + CA_c - P_2C_E \tag{17}$$

where

$$g(A_c) = P_1\sum_{i=1}^{12} g_i(A_c)E_{Ni} \tag{18}$$

$$C = P_1(C_{PV} - C_{E1})\sum_{i=1}^{12}\eta_i\overline{H}_{Ti}N_i - C_AP_2 \tag{19}$$

It is assumed here that cost C_E is distributed to the area A_c and then included in the cost C_A, so that C_E in Eq. (17) can be set equal to zero.

LCS may have an optimum value for some area A_c, which, in this case, must be the root of the following equation

$$\frac{\partial \mathrm{LCS}}{\partial A_c} = g'(A_c) + C = 0 \tag{20}$$

where

$$g'(A_c) = P_1\sum_{i=1}^{12} g_i'\eta_i\overline{H}_{Ti}N_i \tag{21}$$

and

$$g_i' = \overline{\beta}_if_i' + (1 - \overline{\beta}_i)h_i' \tag{22}$$

Since φ' is a monotonically increasing function of λ, and λ decreases with the increase of A_c, it follows that φ' decreases with the increase of A_c. Therefore the maximum numerical value of $g'(A_c)$ is reached at $A_c = 0$. $g'(A_c)$ is therefore a decreasing function of A_c, and $g(A_c)$ is a convex function with $g'(0) > 0$.

3. Discussion of results

The numerical results presented here are obtained for a plant with 54 kW diesel engine connected to amorphous silicon panels manufactured by ASE GmbH. The location considered is Florianópolis (21.6°S/48.5°W) in Brazil. Fig. 1 shows that the life cycle savings have a maximum for the particular panel cost equal to

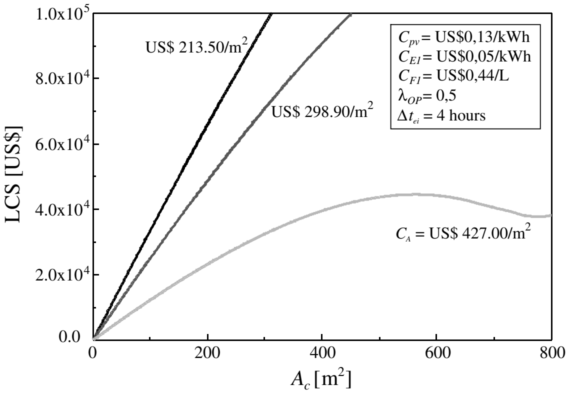

Fig. 1. Life cycle savings as a function of the total panel area, for different panel costs in terms of unit area (the yearly average of the efficiency of the panles is assumed to be 6%).

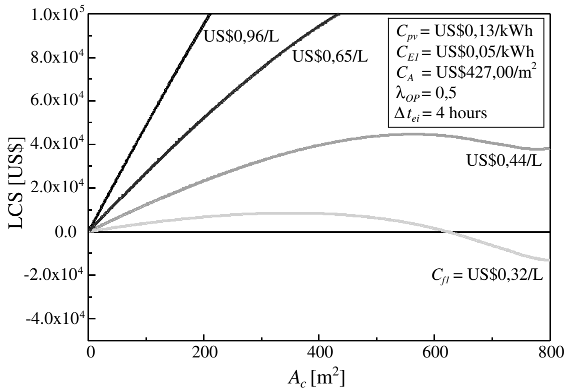

Fig. 2. Life cycle savings as a function of the total panel area, for different fuel cost values.

US\$42,700/m^2. For lower costs the life cycle savings is much higher and increases with the panel area. The engine was supposed to operate at half the value of its nominal operating power ($\lambda_{\mathrm{op}i} = 0.5$), during 4 h a day.

Fig. 2 shows the life cycle savings function for different fuel costs. It is seen that low values of the fuel cost correspond to higher values of the savings. As in Fig. 1, the saving function has maximum values for the fuel cost equal to US\$0.44/l (market price) and US\$0.32/l. The parameter that determines the behavior of LCS is the cost constant C given by Eq. (19). It can be seen that if $C < -g'(0)$, then LCS increases with A_{c} and it can be optimized.

4. Conclusions

In this paper an analytical tool for economical evaluation and optimization of hybrid diesel-photovoltaic plants is developed. The parameter that characterize the optimization cases which is named as the cost constant, is defined in terms of the costs involved as well as the annual energy input generated by the photovoltaic plant. It is also shown that the operating power fraction of the EDG in partial operation is meaningful, as a parameter for decision making, in replacing diesel generation by photovoltaic. For the case analyzed here, the energy revenue value for which photovoltaic generation becomes more profitable and attractive than diesel generation, is correlated with the capital cost, for a specified or optimized panel area.

Acknowledgements

The authors are indebted to CNPq—National Council of Scientific Research/Ministry fo Science of Technology and to ANEEL—National Electrical Energy Agency of Brazil for support to the present work.

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