ISOLATED HYBRID PV-DIESEL POWER PLANTS DESIGN METHOD

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ABSTRACT

The present work shows a methodology to analyse the performance of a hybrid PV-Diesel isolated system in terms of several design and economic parameters. The economic analysis is carried out using the life cycle savings method (LCS). It is shown that for the situation in Northern of Brazil the economy for the application of PV in this kind of systems is favourable. Optimal sizes of PV-arrays may be identified. A respective computer program, which simulates the operation of the hybrid electrical power plant on an hourly basis, was developed and can be a useful tool to design a system, and to provide information for incentive policies.

Introduction

In several regions, mainly in developing and undeveloped countries, there are isolated communities that are not reached by the utility grid. In these locations, one of the most usual solutions for the electricity supply is the installation of small power plants using diesel electrical generator sets (gen sets). In most of these cases diesel supply is very expensive due to the difficulties in transporting diesel from the producing plants to the isolated communities, and sometimes, the substitution of part of the diesel-generated electricity by solar PV panels can be economically attractive (Rüther et al., 2000). However, the optimum size of the PV system is affected by many design variables such as economic parameters, solar radiation available in the location, and the technical specification of the PV and the diesel gen set.

Previous works on the performance analysis of grid connected PV-systems and hybrid PV-Diesel systems are given by Colle et al. (1999, 2001, 2001). In theses works, solar radiation data are applied on a monthly basis. The work from Seeling-Hochmuth (1997) shows a more detailed analysis, where an optimization of a hybrid system is carried out, including not only the PV panels and the diesel gen set, but also batteries, battery charger, wind generator and inverter.

In the present work the simulation of the hybrid system is extended to an hourly basis and several design and economic parameters are taken into consideration. The results presented are given for different operational strategies, where some of the parameters are changed to show their influence in the performance of the system. The basic configuration of the proposed hybrid system is shown in Figure 1. For the calculations discussed in this paper, the

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use of two identical diesel gen sets is considered. The PV arrays are described as a unique system.

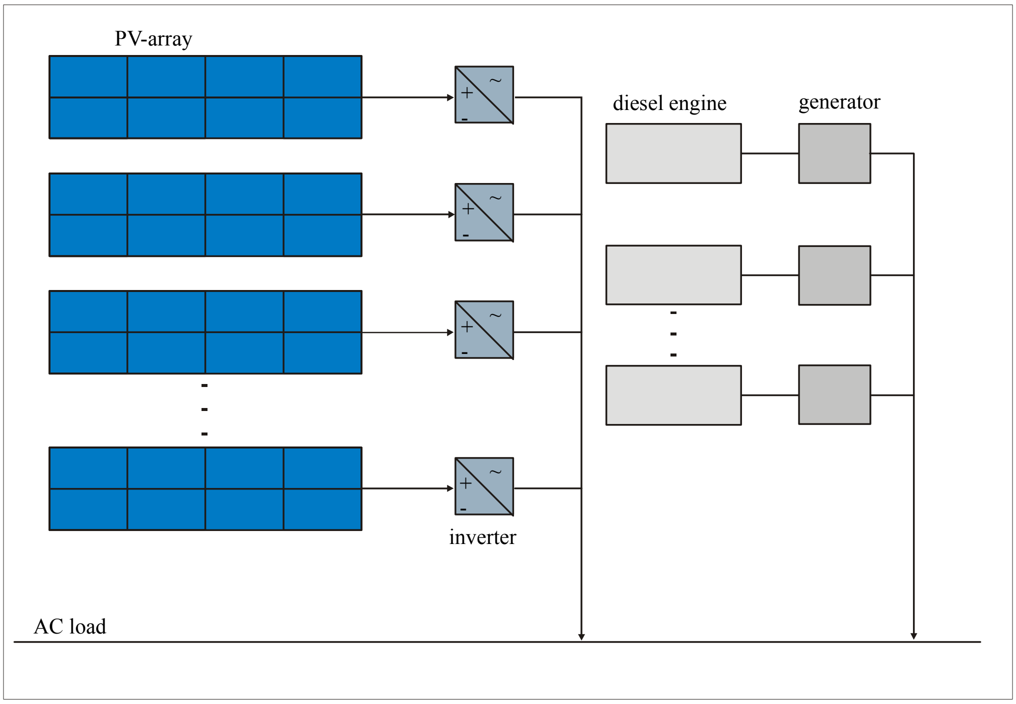

Figure 1. Schematic diagram of the hybrid PV-diesel system

Basic formulation and economic analysis

The modelling of the PV-array is based here on the simple assumption that the instantaneous PV-generated power will be proportional to the solar radiation incident into the panels' surface, i.e. the efficiency of the PV-system (including the inverters) is constant. The instantaneous PV-generated power can be represented as shown:

$$\dot{E}_{PV} = \eta A_{PV} \dot{I}_T = P_{STC} \cdot \dot{I}_T / 1{,}000 \ \text{[W/m}^2\text{]} \tag{1}$$

where $\dot{E}_{PV}$ is de instantaneous PV-generated power [W], η is the average efficiency, A_{PV} is the PV area, $\dot{I}_T$ is the solar radiation [W/m^2] and P_{STC} the nominal peak power in watts at Standard Test Conditions – STC (irradiation = 1,000 W/m^2, cell temperature = 25°C, spectral distribution AM = 1.5) of the PV-systems. The consideration of a constant efficiency is a reasonable assumption for some kinds of PV-cells, but the introduction of more complex models that take into consideration the temperature dependence of the PV-cells can improve the expected results (Rüther, 2001).

In this hybrid diesel-PV system without storage, the diesel gen sets have to balance the PV production and the demand of the load:

$$\dot{E}_{op} = \dot{E}_{demand} - \dot{E}_{PV} \tag{2}$$

The respective load fractions, defined as the ratio between the output of the gen sets to their nominal capacity, are thus given by.

$$\lambda_{op} = \dot{E}_{op} / \dot{E}_{nominal} \tag{3}$$

$$\lambda_{demand} = \dot{E}_{demand} / \dot{E}_{nominal} \tag{4}$$

where λ_{op} is the operational load fraction of the diesel gen sets. λ_{demand} gives the load fraction of the diesel gen set for a diesel only operation. Here, the load fraction λ is always related to the nominal power $\dot{E}_{nominal}$ of one of the gen sets.

Diesel consumption and savings

The main operational cost of this kind of installation corresponds to the fuel costs and one part of the savings comes from it. The specific diesel consumption is a function of the load fraction and its variation is taken into account in economic analysis later in this paper. One of the curves which best fits with a great number of commercial diesel gen sets follows (Colle et al. 2001):

$$\chi(\lambda) = a_0 / \lambda + a_1 (1 - e^{-a_2 \lambda}) \tag{5}$$

where $\chi(\lambda)$ is the specific diesel consumption (kg/Wh) and a_n are the regression coefficients of the curve, which varies depending on the selected diesel engine. As the economic analysis is conduct in terms of nominal power of the diesel gen set, both sides of Eq. (5) must be multiplied by λ. The new curve of the diesel consumption is expressed as follows:

$$\varphi(\lambda) = a_0 + a_1 \lambda (1 - e^{-a_2 \lambda}) \tag{6}$$

If more than one gen set is used, a scheme for the distribution of the total load fraction λ_{op} to the individual load fractions of the various gen sets must be set up to enable the determination of the fuel savings during the simulation. Considering two gen sets, the following simply scheme assuming three cases (A-C) was applied.

- Case A: $\dot{E}_{op} \le 0$ - in this case all energy comes from the PV-panel and part of it could not be used (supply > demand).
- Case B: $0 < \dot{E}_{op} \le \dot{E}_{nominal}$ - in this case one gen set works in a load ratio equal to λ_{op}
- Case C: $\dot{E}_{no\min al} < \dot{E}_{op} \le 2\dot{E}_{nominal}$ - in this case the first gen set works at full capacity and the second in a load ratio equal to $\lambda_{op} = \lambda_{op} - 1$

In all cases above, it is considered that at load zero the diesel engines are kept working, ready to come in operation if suddenly the solar radiation drops. This problem could be generalized for a higher demand and a greater number of gen sets working in parallel.

The fuel consumption during a typical year of operation can be estimated by the sum of the hourly expenses (Eq. (6)) for both gen sets.

$$G(\lambda) = \sum_{year} \varphi(\lambda)\dot{E}_{nominal} \tag{7}$$

The fuel savings correspond to the difference between the diesel consumption with and without the PV-array.

$$G^*(\lambda) = \sum_{year} (\varphi(\lambda_{demand}) - \varphi(\lambda_{op}))\dot{E}_{nominal} \tag{8}$$

Premium tariff for the PV-generated electricity

A number of incentive schemes, to support a more widespread use of PV worldwide, have been proposed and are in practice in many parts of the world, mainly in developed countries. One of the most effective ways of translates government subsidies into effective results is the legally binding buy-back rates, in practice for example in the German 100,000 roofs project (Erge et al., 2001 and Gabler 2001). In these subsidy schemes a premium tariff is paid for PV-generated power to help establish the technology and lead to the economies of scale necessary for PV to become a viable option.

In Brazil such scheme is available, but it has not been extensively used so far. The so-called "valor normativo" – VN is a buy-back rate that allows an IPP (Independent Power Producer) to feed into the public grid all the power produced by a grid-connected generator for a premium rate (ANEEL, 2001).

Life Cycle Savings - LCS

The economic analysis is based on the Life Cycle Savings (LCS) using the $P_1 - P_2$ method (see Duffie and Beckman (1991). In this method, P_1 is the present worth factor of the life cycle energy savings, and P_2 is the ratio of life cycle costs incurred due to the additional investment to the initial investment in the hybrid system. In the present analysis it was considered an investment in which the money is available, there is inflation of the fuel and a market discount rate resulting:

$$P_1 = \frac{1}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^n\right] \text{if } i \neq d \text{ or } P_1 = \frac{n}{1+i} \text{ if } i = d \text{ ; and } P_2 = 1 \tag{9}$$

where d is the market discount rate and i is the inflation rate.

The LCS of the hybrid PV-Diesel system is calculated considering that the savings come from the decrease in the diesel consumption and from a premium tariff for PV-generated power. The additional costs of the PV-system are also taken into account in this evaluation. The LCS for the present analysis is expressed as follows:

$$\begin{aligned} LCS = & P_1(\overbrace{C_{F1}G(\lambda)}^{fuel\_savings} + \overbrace{(C_{PV} - C_{diesel})E_{PV}}^{premium\_tariff}) \\ & - P_2(\overbrace{C_W \dot{E}_{PV,peak} + C_E}^{additional\_capital\_investment}) \end{aligned} \tag{10}$$

where C_{F1} is the unit fuel cost [US\$/kg], $G(\lambda)$ is the annual fuel consumption function [kg], C_{PV} is a premium tariff for the PV-generated electricity [US\$/J], C_{diesel} is the tariff for the diesel-generated electricity [US\$/J], E_{PV} is the annual PV-generated electricity, C_W is the unit installation cost [US\$/Wp], $\dot{E}_{PV,peak}$ is the nominal peak power of the PV installation (P_{STC}) [Wp] and C_E represents others costs of the installation.

RESULTS

To show the capabilities of the present methodology, some possible scenarios are presented, where interesting conclusions can be drawn.

The demand of the hybrid system varies during the day. In the simulations shown here a constant base load, which is extended to a peak load during a chosen period of the day is considered.

The basic technical data from the PV-system and the gen set are taken from commercial equipment, the prices and economic parameters are for Brazil. These data are the following:

- PV panel – Unisolar US-64 (rated power = 64 W), global efficiency of the PV-system (including inverters) – 5.48%;
- gen set – Deutz - BF4M1012E, nominal power – 54 kW, constants of the consumption characteristic curve as given in Eq. (6) $a_0 = 47.77$ [kg/Wh], $a_1 = 198.42$ [kg/Wh], $a_2 = 1.86$ (dimensionless);
- daily consumption profile:
    - 1-10h and 14-24h: 81 kW
    - 10-14h: 91.8 kW
- cost per power unit of the PV-system – US$ 4,52 / Wp;
- buy back rate of PV-generated electrical energy – US$ 0,13 /kWh (ANEEL, 2001);
- buy back rate of diesel generated electrical energy – US$ 0,05 /kWh (ANEEL, 2000, North Region of Brazil, 2000);
- cost of diesel – US$ 0,44 /liter (US$0,52 /kg);
- period of analysis – 20 years;
- annual inflation rate – 10%;
- annual market discount rate – 8%.

The solar radiation data used in the simulations is a TMY-Typical Meteorological Year derived from data measured in the city of Florianópolis – Brazil (27°36'S / 48°30'W) (Abreu et al., 2000). The annual radiation sum at this location is close to 5,700 MJ/m^2 (1,600 kWh). This data set was chosen due to the availability of hourly irradiance data. It is however not located in North region of Brazil and its radiation sum is about 15 % smaller than in that region. Thus the results presented are conservative in the sense that the PV-production is underestimated.

Figure 2 shows the results obtained with the data above. It can be seen that for this case there is an optimum array size around 110 KWp and it is also shown that there is another peak in LCS near an array size of 30 kW$_p$.

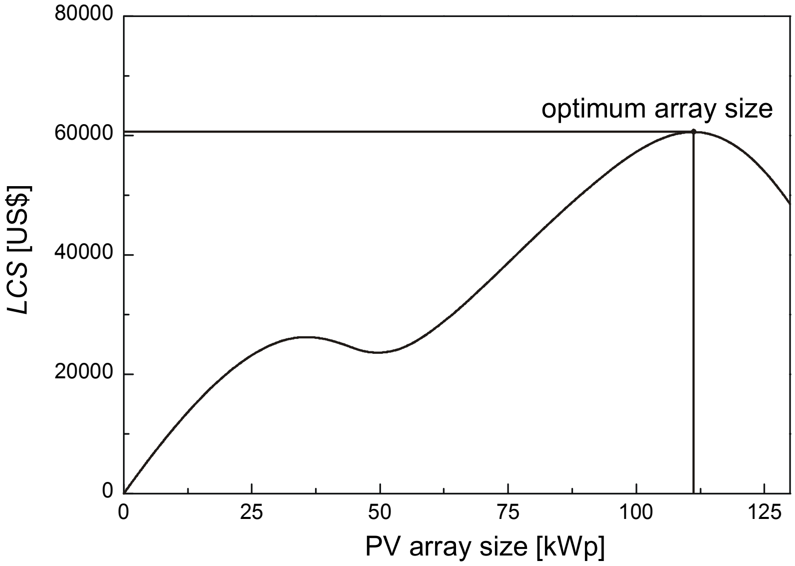

Figure 2. Life cycle savings as a function of the PV-array size.

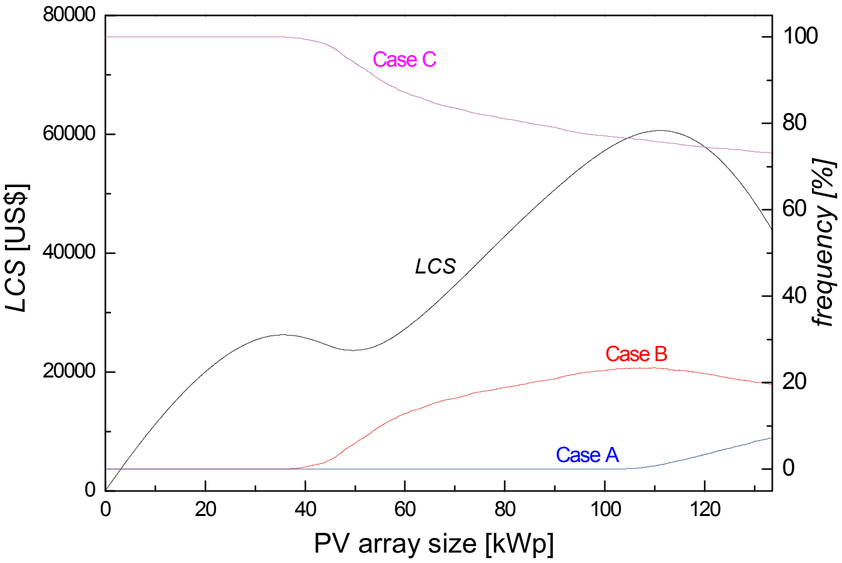

Figure 3. Frequency of each different case as a function of the PV array size.

Observing the frequency of occurrences of cases A-C plotted in Figure 3, it can be seen that the LCS increases with the array size until the first engine starts to work without load (switch from case C-B). The specific diesel consumption during these periods is high and there is no additional economic gain in increasing the array size. This also could be seen in Figure 4, where the different portions of the Eq. (10) are plotted separately.

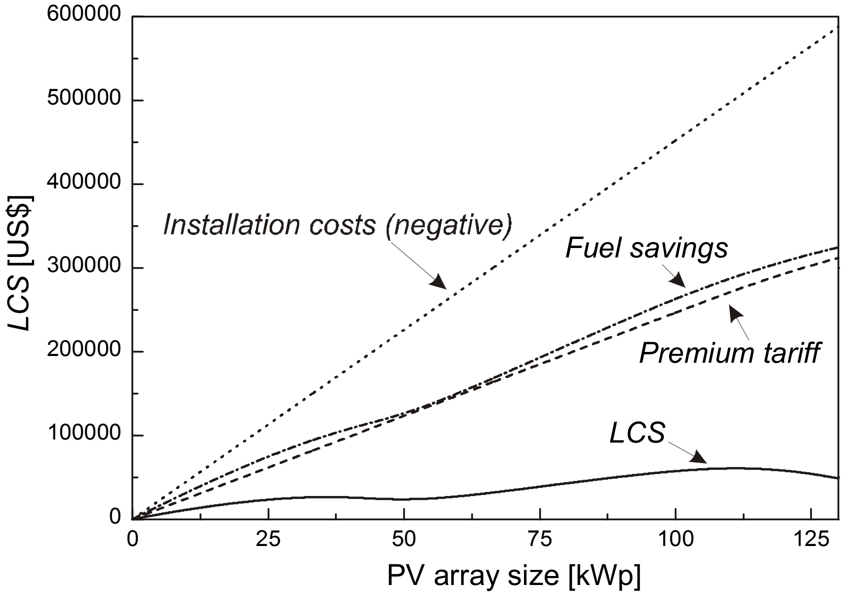

Figure 4. Individual contributions of the different terms in the Life Cycle Savings.

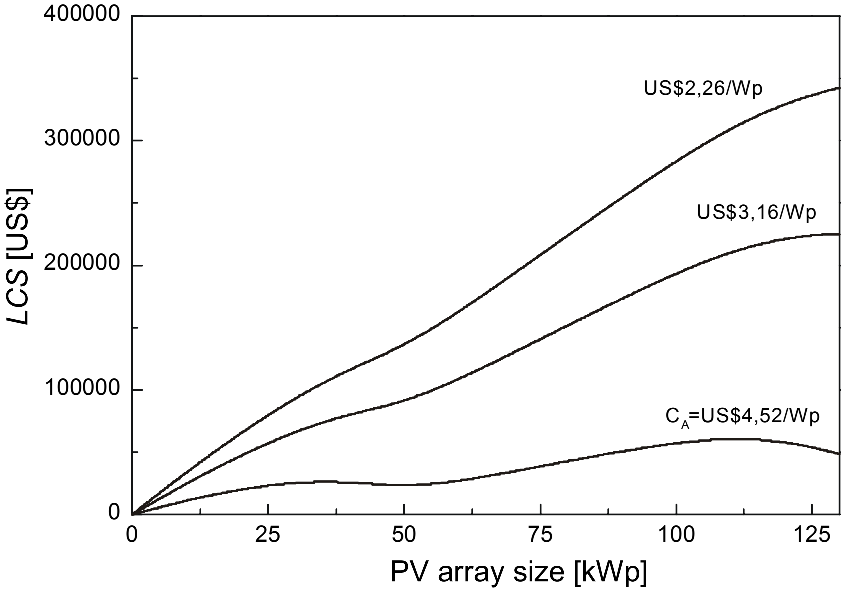

Figure 5. Life cycle savings as a function of the PV-array size for different costs of the PV system.

Keeping all but one parameter, the sensitivity of the LCS related to each parameter may be analyzed.

In Figure 5 the results for the variation of the price per Wp of the PV system is shown. With 30% cheaper panels the first relative optimum disappears and the optimum area is bigger. As the price decreases, the LCS tends to be linear with the array size until the moment that no more fuel is saved (all gen sets working without load).

Figure 6 refers to the case of a change of the base load, described here by the load fraction ($\lambda_{demand} = \lambda_{demand} - 1$) of the second gen set. The peak load is kept constant. The behaviour of the curves is similar but the first relative optimum is not so pronounced for the higher λ_{demand}.

This occurs because the hours where the first gen set works with low load (high specific consumption) are balanced by the fuel savings of the second gen set at other times.

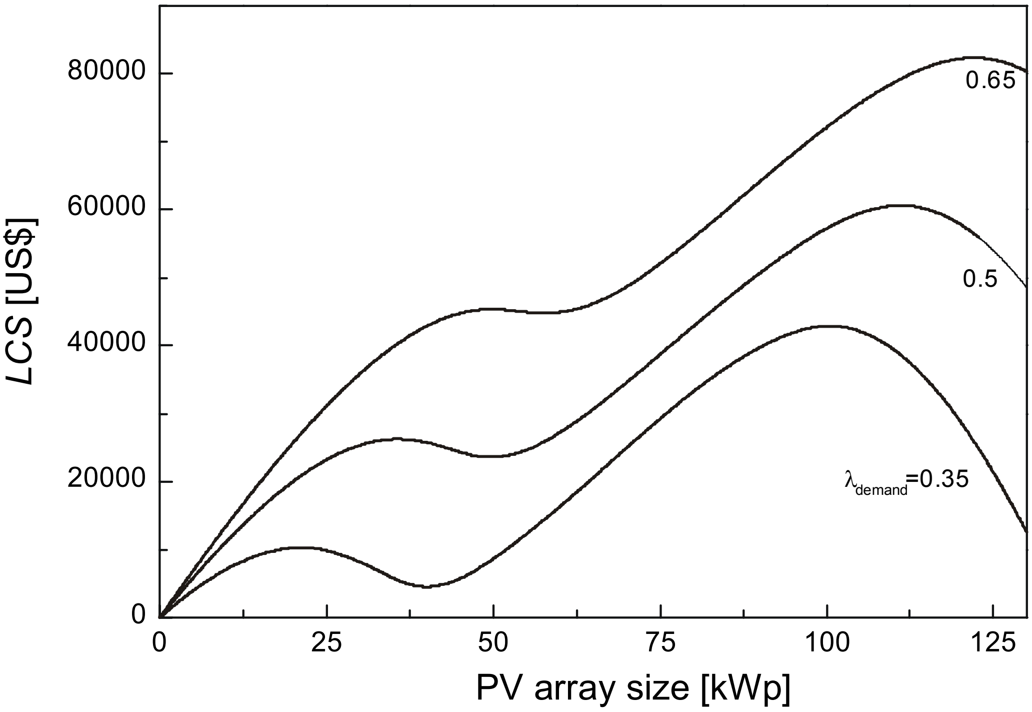

Figure 6. Life cycle savings as a function of the PV-array size for different loads of the hybrid system.

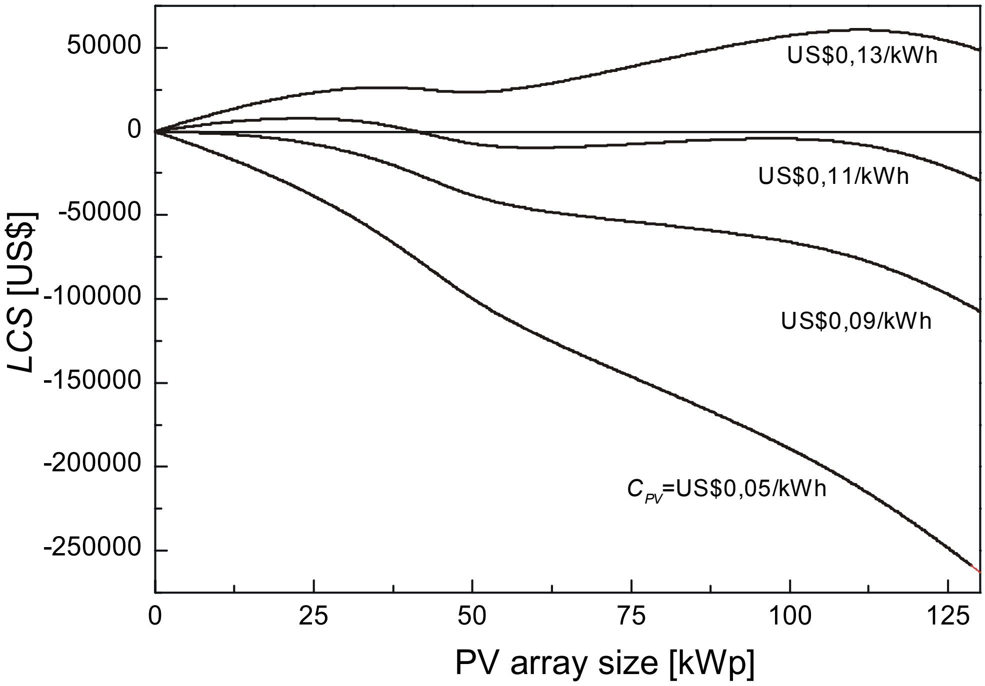

Figure 7. Life cycle savings as a function of the PV-array size for different Premium tariffs.

The influence of the premium tariff in the analysis is shown in Figure 7. The existence of a premium tariff is actually necessary to the economical viability of the PV system. For each particular hybrid system to be designed there is a different premium tariff, therefore its value must be defined taking into account the peculiarities of the power plant to achieve equivalent results in the economical analysis.

Conclusions

The case study analysed shows the existence of favourable conditions – both in view of radiation resource and the tariff structure – for isolated grid PV-diesel applications in Brazil. Procedures for the analysis of the hourly system performance have been developed to identify the optimum PV-array sizes. They may also be used to study the influence of the PV system costs, the load to be supplied and the tariff structure on the economic figures on the respective configurations. For the general applicability, they in the future will be linked with procedures to derive hourly meteorological time series from available monthly data (see e.g. Becker et al., 2001).

The next step of the present research will be the validation of the proposed methodology using real operation values measured in a hybrid system located in Araras – Brazil (10°04'S / 65°20' W).

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