A MONTHLY AVERAGE SOLAR IRRADIATION BASED ALGORITHM TO ACCESS THE LIFE COST SAVINGS OF PHOTOVOLTAIC – DIESEL HYBRID POWER PLANTS FOR ISOLATED GRIDS

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Abstract

In the present work the simulation of the hybrid system is extended to an hourly basis from a monthly average solar irradiation basis. The solar irradiation data are taken from the SWERA database for Brazil. The data are converted to monthly means of global irradiation incident on tilted surface of the PV panels. The monthly based algorithm is based on a best fitting against the hourly based life cost savings obtained from economical analysis carried out in a previous work. The cost of the raw oil price, oil subsidy, transportation cost, PV revenue factor, inflation and other minor cost are considered for particular Brazilian situations. The simulation is carried out in the MATLAB simulating programming environment. The hourly based life cost saving is plotted against the monthly based extension for three locations the Brazil. The hourly total of global solar irradiation is derived from TMY data sets of SWERA, as well as from a BSRN station. A Brazilian mapping of the life cost savings is presented, for a single diesel engine of 106 kW and installed PV array of 79.04 kW_p. The obtained results show a good agreement between the monthly based and hourly based life cost savings for twenty locations (capital cities) of Brazil.

1. 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 electricity supply is the installation of small diesel electric generator sets (gen sets). In most of these cases diesel supply is very expensive due to the difficulties of diesel transport from the producing plants to the isolated communities, and sometimes the substitution of part of the diesel-generated electricity by solar photovoltaic panels can be economically attractive (Rüther et al., 2000). Not to mention the achievable reduction of CO_2-emissions in respect of air pollution and global warming occurring today is an essential enhancement. However, for economical evaluation the optimum size of the PV-system is affected by many design variables such as the location's available solar irradiation, and the technical specification of the PV panels 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. The solar irradiation data is given on a monthly basis, which at the moment is the most applicable form of data for Brazil as concerns reliability and data coverage throughout the nation. For instance, the used source for monthly global irradiation is provided by Pereira et al. (2006). As comparison for the life cycle savings calculation has been elaborated a second model by Abreu et al. (2003), which compared the hourly irradiation incident at the location of Florianópolis. The results of the two algorithms are given in Figure 1.

One can observe different values for the LCS for the two approaches. In order to identify the reasons for the discrepancy and to thereby develop a monthly irradiation based algorithm a numerical tool is implemented which is able to derive results which, on the one hand, are comparable with the ones of the hourly evaluation in terms of correctness and, on the other hand, are dependent on accessible and reliable data such as the monthly global irradiation. Following the methodology shown in Felten et al (2008). new results are presented in the present work.

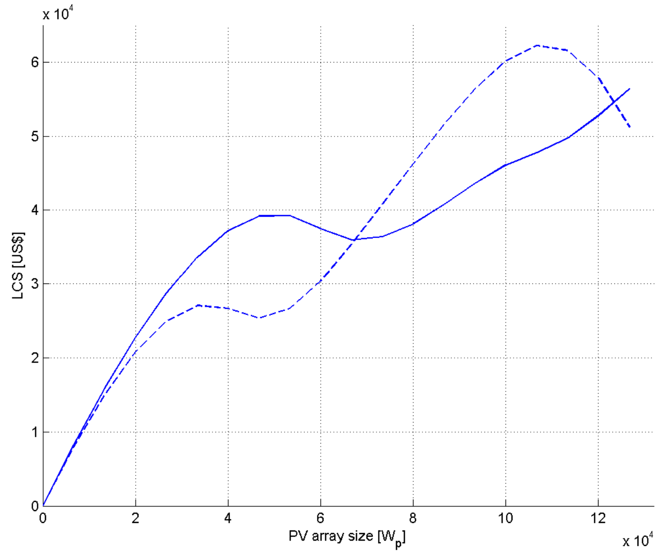

Figure 1. Life Cycle Savings (LCS) as function of the installed nominal power of the photovoltaic modules [W_p], monthly and hourly irradiation based evaluation for two diesel gen sets and the location of Florianópolis (straight line – monthly evaluation; dashed line - hourly based evaluation).

2. THE MODEL

The model taken into consideration by Colle et al. (2001) and Abreu et al. (2003) as well as for the described work is a first level approach, it assumes that all power that is supplied by the PV-array does not need to be supplied by the diesel gen sets as shown in the scheme of Figure 2.

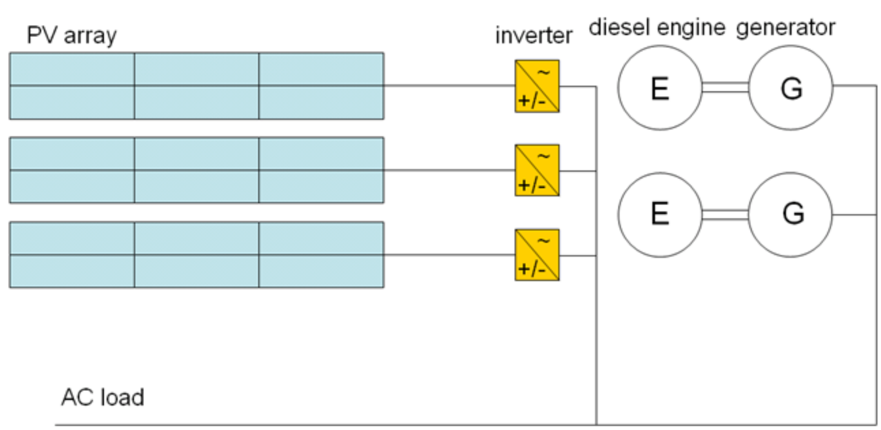

Figure 2. Sketch of the considered modules of the former models and the actual

According to the given scheme and the life cycle savings theory provided by Duffie et al. the LCS[US$] are given by:

$$LCS = P_1(c_{diesel}\Delta G_{diesel} + (c_{energia,pv} - c_{energia,diesel})\Delta E_{pv}) - P_2 c_{pv} P_{pv,tot}$$

where P_1[-] and P_2[-] are determined factors for the simulated scenario (20-year-period, no loan). c_{diesel}[US$/kg] is the specific cost of diesel, ΔG_{diesel}[kg] is the annual amount of diesel savings, $c_{energia,pv}$[US$/kWh] and $c_{energia,diesel[[}$US$/kWh] are the achieved market prices for photovoltaic respectively diesel energy, ΔE_{pv}[kWh] is the annual amount of PV-energy supplied to the grid, c_{pv}[US$/W] is the specific cost of installed PV-power and $P_{pv,tot}$[W] is the installed nominal PV-power. All cost/price factors as well as the annual PV-energy ΔE_{pv} and the nominal PV-power $P_{pv,tot}$ has not been altered for the monthly and the hourly evaluation. Thus the fuel savings ΔG_{diesel} needed to cause the discrepancy.
The fuel savings ΔG_{diesel} are closely linked to the function of specific consumption φ[g/kWh] of the diesel engine, which – according to Colle et al. (2001) and Abreu et al. (2003) is given as follows:

$$\varphi = \frac{\dot{m}}{P_{nom}} = a_0 + a_1\lambda(1 - e^{a_2\lambda})$$

The specific consumption is the mass flux of diesel $\dot{m}$ divided by the nominal power of each engine P_{nom} and is dependent on three engine characteristic coefficients a_0[g/kWh], a_1[g/kWh] and a_2[-] and the load fraction λ.

$$\lambda = \frac{P_{load}}{P_{nom}}$$

Here is Pload the work load of the diesel engine. The specific consumption is a highly non-linear function of the load fraction, which built the focus of the present work. The annual fuel savings for one engine scale with the integral of the difference between the specific consumption the diesel engine without PV-support (φ_{diesel}[g/kWh]) and the one for the hybrid plant (φ_{hybrid}[g/kWh]) over the time of the year.

$$\Delta G_{diesel} = P_{nom} \int_0^{8760h} \varphi_{diesel}(t) - \varphi_{hybrid}(t)dt \qquad (4)$$

For several engines this can be done in analogy (see Colle et al.). The load fraction is calculated by

$$\lambda = \frac{d\Delta t - S}{P_{nom}\Delta t} \qquad (5)$$

Here is d[W] the demand and S[W] the energy that is supplied in one time step by all solar panels. For the hybrid plant S is greater than 0, for the diesel-only plant it equals 0. Δt is the according time step of the evaluation (one hour or total hours of the month).

3. COMPARISON OF THE MONTHLY AND HOURLY EVALUATION

The difference between the two systems lays in the deviating numerical resolution of the integral in Equ. (4) and the numerical resolution of Eq. (5) respectively. For the monthly evaluation the amount of energy S_i[Wh] for the month i is regarded.

$$S_i = \eta_{sol}\overline{H}_{T,i}N_iA_{pv,tot}$$

η_{sol}[-] is the efficiency of the panels, $\overline{H}_{T,i}$ [Wh/(m^{2}d)] is the monthly average daily irradiation on a tilted surface, N_i[d] the days of the according month i and $A_{pv,tot}$ [m²] the total surface area of the tilted panels. Colle et al. introduced as well a mid day peak factor $\overline{\beta}_{T,i}$, which took into consideration the stronger irradiation around solar noon for the amount of n_i[h] hours. Without loss of generality for the given analysis n_i is set to 0 hours.
For the hourly evaluation the amount of energy supplied by the solar panels within the hour j is S_j[Wh].

$$S_j = \eta_{sol} I_{T,j} A_{pv,tot}$$

Here is $I_{T,j}$[Wh/m²] the hourly irradiation on a tilted surface. The more exact distribution of the load fraction λ caused by the different numerical resolutions of the irradiation causes the main effect on the life cycle savings.

4. CONVERSION METHODS: MONTHLY TO QUASI-HOURLY EVALUATION

In order to compensate the influence of the monthly resolution of irradiation data, which is – for the localization of Brazil – the most reliable and accessible, there have been developed two conversion methods from monthly to quasi-hourly evaluations.

Best Fitting Approach (Method 1)

The empirical method assumes a sin-distribution of the load fraction λ for a constant demand d.

$$\lambda_{cor,\mathrm{var}} = \lambda_{\max} - \lambda_{amp}(w_0 \sin x + w_1 \sin^2 x + w_2 \sin^4 x + w_3 \sin^6 x)$$

The index "cor" stands for "correlation", "var" for "variable". λ_{max} is the load fraction of the engine without solar substitution, λ_{amp} is the amplitude, by which the load fraction drops. Together with $w_{0/1/2/3}$ these are coefficients which needed to be optimized. To each amplitude and set of parameters $w_{0/1/2/3}$ (with $w_0+w_1+w_2+w_3=1$) belongs an average load fraction $\overline{\lambda}$, an average specific consumption $\overline{\varphi}$ and its momentary value $\varphi_{cor,m}$.

$$\overline{\lambda}(\lambda_{amp}, w_{0/1/2/3}) = \frac{1}{\pi}\int_0^{\pi} \lambda_{cor,\mathrm{var}}(\lambda_{amp}, w_{0/1/2/3}, x)dx$$

$$\overline{\varphi}(\lambda_{amp}, w_{0/1/2/3}) = \frac{1}{\pi}\int_0^{\pi} \varphi(\lambda_{cor,\mathrm{var}}(\lambda_{amp}, w_{0/1/2/3}, x))dx$$

$$\varphi_{cor,m}(\lambda_{amp}, w_{0/1/2/3}) = \varphi(\overline{\lambda}(\lambda_{amp}, w_{0/1/2/3}))$$

Each combination k of $w_{0/1/2/3}$ and λ_{amp} results in an octuple M_k.

$$M_k = (w_0, w_1, w_2, w_3, \lambda_{amp}, \overline{\lambda}, \overline{\varphi}, \varphi_{cor,m})$$

Then the ratio (for each month i) between the annual fuel savings of the continuous and the average function is:

$$r_i = \frac{\varphi(\lambda_{\max}) - \overline{\varphi}}{\varphi(\lambda_{\max}) - \varphi_{cor,m}} = \frac{\Delta G_{diesel}(\lambda_{cor,\mathrm{var}})}{\Delta G_{diesel}(\overline{\lambda})}$$

If the load fraction for the monthly evaluation equals $\overline{\lambda}$, there must exist an optimum combination of $w_{0/1/2/3}$, so that the product $R_s \Delta G_{diesel,monthly}$ converges towards $\Delta G_{diesel,hourly}$, where R_s is the weighted average ratio over the year.

$$R_s = \sum_{i=1}^{12} r_i \frac{N_i}{365}$$

Here is s the index for the PV-array size. This kind of optimization was done for each of the 20 cities of the SWERA data base as well as for the complete set of them for plants with one and two engines.

Method of Correlating Monthly and Hourly Radiation (Method 2)

In a similar manner a ratio factor can be defined by an approximation of the diffuse and global hourly irradiation from the monthly means. Here is referred to Duffie and Beckman (2001)., who introduced the statistical factors r_t and r_b, which take also into consideration the latitude of the localization by the length of the day. Without optimization of any parameters one can receive a reconstruction of the hourly irradiation from monthly means and finally calculate a conversion factor for the fuel savings. Because the derivation of the hourly values is already published and the idea behind the adaptation of LCS is comparable to the above illustrated, only the results are shown as follows.

5. RESULTS

For the first method was made the attempt to identify a pattern of interdependency of the parameters $w_{0/1/2/3}$ and geographic data of the localization (latitude, altitude etc.). No such correlation was found, local effect like typical midday cloudiness etc. Then an optimization for all of the 20 cities of the SWERA database was run and the results were remarkable. For instance the deviation of life cycle savings between hourly and quasi-hourly evaluation summed up for all 20 cities and each installed nominal PV-power for a plant with two gen sets was less than 5 %. For a plant with one engine the error almost disappears. These issues are illustrated by figures 3 and 4. For the second method the deviation was slightly higher.

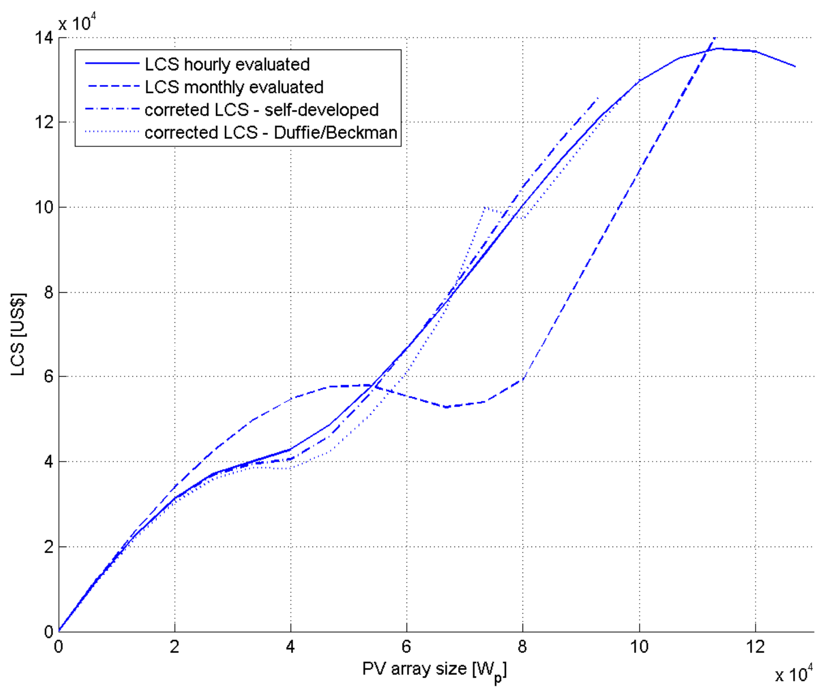

Figure 2. LCS as function of the nominal potential of the photovoltaic arrays; the results calculated on hourly, monthly and quasi-hourly basis of method 1 and 2 are illustrated for setups with two gen sets with the typical meteorological year of Porto Velho

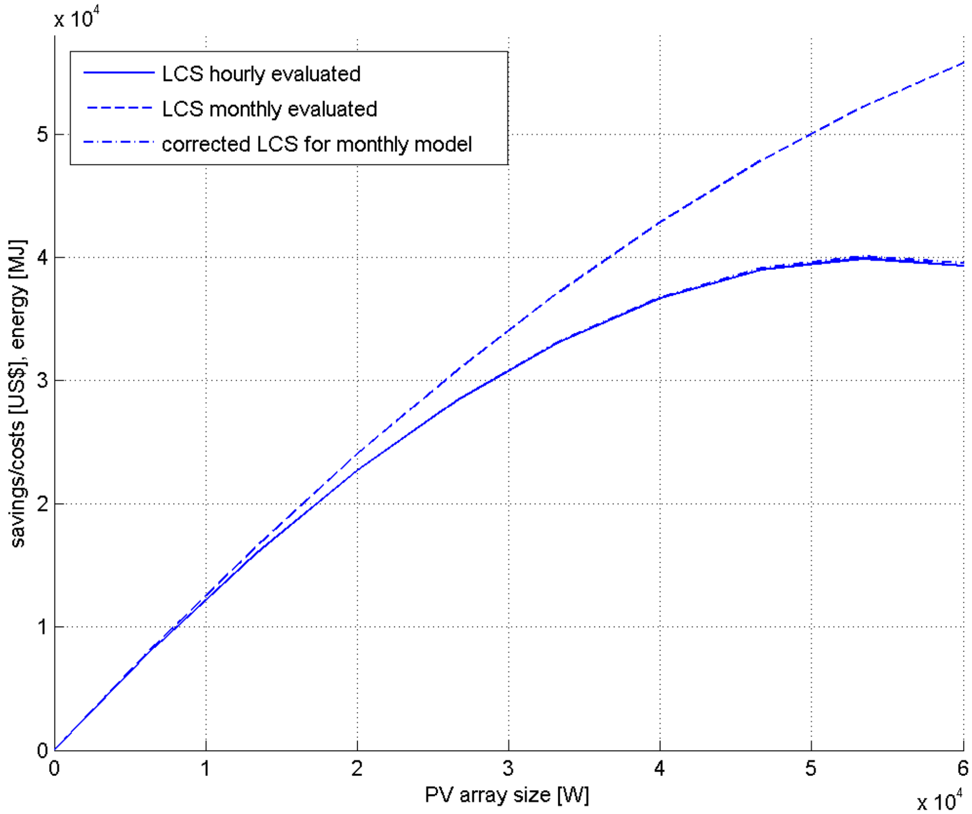

Figure 4. LCS as function of the nominal potential of the photovoltaic arrays; the results calculated on hourly, monthly and quasi-hourly basis of method 1 are illustrated for setups with one gen sets with the typical meteorological year of Florianopópolis.

6. CONCLUSIONS

The present results show inevitably that a conversion from monthly means irradiation towards quasi-hourly calculation of the life cycle savings is possible with a very good accuracy. The first conversion method is applicable for regions where exists a synthetic database as reference and as optimization criteria. It is valid in a bounded geographical region, the more diverse the expansion of the region is (in terms of latitude, altitude, coastal and continental areas) the greater becomes the expectable deviation. The second method is to be used for regions with different localizations apart of any synthetic data. The second method can be seen as autarkic. Nevertheless for restricted geographical expansion of the region, the method 1 with its optimization algorithm bears less deviation.

After all one can say that both methods are suitable to achieve LCS-result of a comparable exactness of the hourly evaluation, only being dependent on more easily-accessible and reliable data like the monthly irradiation.

With the means of method one for the limited meteorological region of Brazil it was possible to produce a map of the life cycle savings. Here fore was used the SWERA database in order to calculate the Life Cycle Savings for a resolution of 100 km x 100 km (Figure 5).

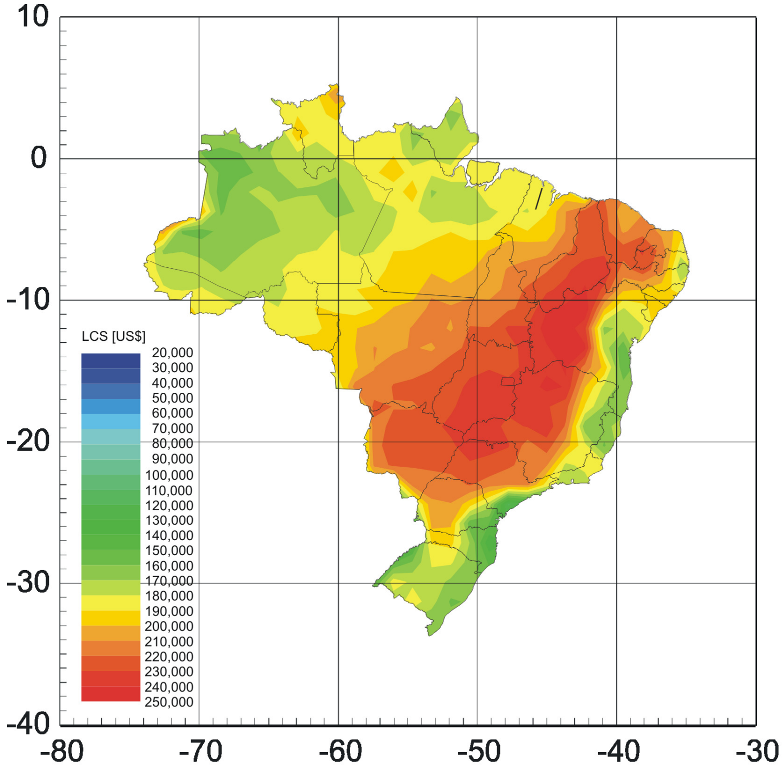

Figure 5. Map of Life Cycle Savings for Brazil.

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