ADDING PV-GENERATORS WITHOUT STORAGE TO MEDIUM SIZE STAND ALONE DIESEL GENERATOR SETS TO SUPPORT RURAL ELECTRIFICATION IN BRAZIL

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Abstract Village electrification in the power range below 100 kW in the Brazilian Amazon is actually based on Diesel generator sets supplying energy to remote local mini- and micro-grids. Some hundred of these systems are in operation. In order to analyse options for the reduction of the respective fuel consumption and thus the associated costs, we are studying the introduction of PV-generation in systems in the power range above 10 kW. More specifically, we assess technical aspects and limitations of adding PV generators without storage to the systems, taking into account the particular load characteristics and meteorological conditions in the region. We present considerations and simulations to discuss the sizing of PV arrays with respect to the fuel savings that can be gained per installed PV capacity. As validation of these calculations, the performance of a pilot hybrid Diesel / PV system without storage that is in operation in the Amazon state of Rondonia is analyzed. Based on the figures for the specific fuel savings established, we present options to turn the high overall potential for this type of PV application economically feasible for the electricity suppliers, and thus increase the PV market in Brazil.

1. INTRODUCTION

In villages far from the utility grids, in many countries the electric energy supply is based on diesel generators or small hydroelectric plants. This is, for example, the case for most of the villages in the northern part of Brazil. In total, an annual consumption of about 40 GWh is supplied by diesel generators in isolated grids with capacities below 100 kW.

Both due to macroeconomic and ecologic reasons, a reduction of this diesel consumption is desirable. Among others the introduction of PV to this market niche is a mean to reach this goal. On the microeconomic scale, however the competitiveness of PV with diesel generation is up to now only proven for systems in the power range of a few kW (see e.g. Bopp et al. 1997). For the power range inspected here, the best and most effective way for the PV application – in the sense of fuel saved per installed PV capacity) – still has to be identified.

An option for this path is demonstrated by a Diesel-PV-hybrid system which confines itself to a limited contribution of PV to the load coverage, but reduces the associated cost for the PV extension of the system by the renouncement of the use of storage. A demonstration system, described by Rüther et al. 2000 and Rüther and Montenegro 2001 is in operation at Araras in the Brazilian federal state of Rondonia in the Amazons region.

To get first a general overview on the fuel saving potential of this concept, the following section will discuss the technical constraints for the fuel savings. A procedure which links representative meteorological data for the region of interest with the performance of PV-diesel-hybrid systems is used for this purpose. In view of a generalization of the findings the system itself is characterized by a set of normalized parameter describing the ratio of the daytime load and the rated power of the diesel generator set. The results are presented as a pair of performance data (reduction of the fuel use with respect to the systems load and PV-yield) for a specified size of the added PV generator.

In view of a validation of these results, the actual performance of the demonstration system is discussed for comparison.

The figures for the obtainable specific fuel savings established by the simulations and the analysis of the field data are used as input to a discussion of the economic potential of PV in this market niche. Here both the actual economic viability and the necessary regulatory framework for a realization of the technical potential are discussed in conclusion.

2. THE TECHNICAL OPTIONS AND CONSTRAINTS

The mini grids under consideration have a capacity in the range of several 10 kW. This is about one order of magnitude higher than the rating of hybrid PV-diesel systems as they are discussed i.e. by Seeling-Hochhuth (1997), Bopp at all (1997) or Muselli et al. (1999). For these systems in the power range of kW, a PV-coverage of the load of more than 50% is discussed. To reach these values, the incorporation of a storage capacity sufficient to cover the load for at least one day is necessary. As stated by Muselli et al. (1999) the life cycle cost for these batteries may be in the range of more than 50% of the life cycle costs of the PV generator.

For the system size discussed here – the demonstration system at Araras has to cover an average load of several 10 kW - in view of the increase of the initial investment due to the battery costs and the problems associated with the operation of battery banks of hundreds of kWh capacity in a 'non technical' environment, it seems reasonable to constrain the analysis to retrofitting with PV to systems without storage. The simplicity of the system however has some drawbacks concerning the possible PV contributions to cover the load as we will discuss in following sections.

2.1 Basic assessment of the benefits from the integration of PV into stand alone diesel systems

To get an impression of the order of magnitude of the fuel savings that may be associated with the addition of a PV generator to a diesel generator set (DGS), one may start with the figure of the specific fuel consumption for the production of one kWh of electricity by the DGS. For a state of the art DGS with a nominal capacity of about 50 kW figures of 0.215 [kg/kWh] are given e.g. by Anonymous (2002). Based on an optimum yield of a PV generator in Brazil, which is in the range of 1500-2000 [kWh/kW] one kW of PV can thus be associated with a fuel saving of about 320 - 430 kg of diesel when replacing electricity from a diesel at optimum operation conditions. These figures are subject to both positive and negative changes when either the DGS or the PV is operated not at their respective optima.

2.2 Constraints for the PV benefits

As mentioned, the data presented above are based on the ideal assumption that all PV energy can be used in the system and that the diesel is always operating at its nominal conditions, i.e. that the load is equal to the nominal load of the DGS and that the contribution of the PV to the load coverage is negligible. In this section the change of the PV benefits due to real operation conditions of the PV generator in the system is discussed. This includes the effects of the operation of the DGS below its nominal load, the need to assure a minimum load to the diesel and the need to dump PV power, when it cannot be used in the system.

2.2.1 Characteristics of the specific DGS fuel consumption

As shown in figure 1, a DGS operated to supply a power less than its nominal value, shows a decreased efficiency and thus an increase of the specific fuels consumption. Based on information given by the manufacturer of a 54 kW DGS (Anonymous 2002) parameters for an analytic model of the fuel consumption have been extracted by Colle et al. (2001).

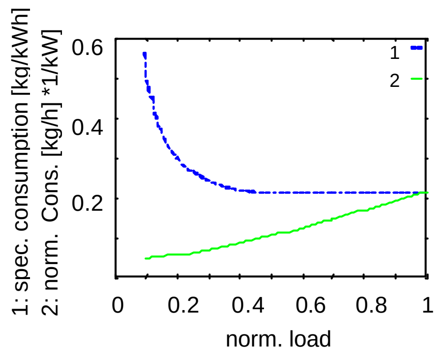

Fig. 1: Characteristics of the fuel consumption of a diesel generator set DGS. Given are the absolute (lower curve) and specific fuel consumption in dependence of the diesel loading. Both the load and the fuel consumption are given in a form normalized to the nominal power output of the system. Data are taken from manufacturers data sheets (Anonymous 2002).

As discussed e.g. by Infield (1988) or Beyer et al. (1995) the fuel savings per kWh of avoided load will decrease with decreasing load due to the shape of the consumption curves. Under the no-load condition the diesel consumption will remain at about 20% of its nominal value.

2.2.2 Constraints due to a necessary minimal diesel load

As a second constraint, it must be taken into account that it is not recommendable that a DGS is operated at load below ~0.15 of its nominal power. This value may also be recommended to secure the electrical stability of the grid formed by the generator of the DGS. As a consequence for systems without storage, PV power has to be dumped in the case that the effective load (load – PV power) is pushed to this boundary. This affects again the fuel savings. A reduction of these losses however can be achieved by splitting the total DGS capacity into several units with at best unequal sizes, together with the appropriate scheduling. By this, the required minimal load can be reduced to that for the smallest of the diesel units.

2.3 Load conditions for DGS in small stand alone systems

Due to the facts discussed above, knowledge of the load characteristics that goes beyond a figure for the average load is needed. Examples of time series of the temporal evolution of the load for the type of system discussed are used by e.g. Musselli et al. (1999), van Dijk (1995) and Ashari and Nayar (1999). An approach towards a parameterised model is used by Vernetti and Kleinkauf (1999) where a procedure to generate time series of hourly load is discussed. This model is based on empirical data from two DGS systems and partly relies on tabulated values of normalized average time series. From this model the information on the temporal evolution of the load may be gained for a given value of the monthly average load. According to the data presented, it can be deduced that the maximum load – which determines the nominal power of the DGS system - occurs in the evening hours. The average load during the daytime - for the systems analysed (one in Jordania and one on an island in the Atlantic Ocean.) - is typically in the range on ~0.2 - 0.5 of the maximum load. These values are in a qualitative agreement with information given by the other papers on wind diesel systems cited above. It should however be mentioned, that this information is still based on a very limited number of examples.

In the following section the analysis of the benefits from a PV generator without storage is restricted to the daytime hours. As will be exp lained in section 3.2.2 a simplified model is used to model the load characteristics for these hours.

3. CALCULATION SCHEME FOR THE PV BENEFITS

As the fuel consumption shows a high sensitivity to the variation of the operation conditions, the system performance must be analyzed with a time resolution of at least one hour to get a realistic assessment of the fuel use and the PV yield. This demand on the time resolution of the database used is discussed extensively in the literature on wind-diesel systems (DGS and wind turbine) (see e.g. Degner, 1997). Accordingly we use a simulation model working on an hourly time base, which will be shortly explained in the following sections.

3.1 The simulation model

For the simulation, a model for daytime operation of a simple PV-diesel-hybrid system is implemented in the simulation tool INSEL (Luther and Schumacher 1995). Given load and radiation data, the values of the diesel fuel consumption and the useful PV production are calculated on the hourly time base. For this, the following specific models are used.

In agreement with the PV technology applied for the demonstration system (see Rüther and Montenegro 2001), for the PV output a model for a generator composed of a-Si Modules is used (Beyer et al. 2001). This model is derived from measured performance data of a 2 kW system. For the DC/AC inverter, the efficiency versus part load characteristic taken from a standard commercial model is used. The fuel consumption is calculated using the efficiency model of a standard DGS as given in figure 1. A control that assures a minimal load of 0.15 times the nominal power for the diesel by dumping the excess PV power is implemented in the simulation model. In case of the application of several units, a tool for the scheduling would additionally have to be applied here

The assumption of a single unit is taken here to keep the simulations close to the pilot system, were effectively only one diesel is in operation. The fuel savings estimated this way are thus in general somewhat conservative, as the possible benefits of the use of several units as mentioned above are neglected.

3.2 Input data

3.2.1 Radiation data

For the simulation both radiation and load data with hourly time resolution must be available. For the general assessment of the fuel saving potential of the technology analysed, the simulation should not be limited to locations disposing of a set of measured meteorological data. Therefore we use a procedure to generate synthetic hourly time series from data files with monthly averages, which are more abundant.

As basic input for the radiation data in the inspected region, a solar radiation Atlas for Brazil is available (Colle and Pereira, 1998). The atlas gives, with a special resolution of ~ 50km x 50km (0.5 x 0.5 °), data of the monthly means of the daily radiation sum on the horizontal surface. Using the methods described by Beyer et al. (1994) and Becker et al. (2001), hourly time series are generated from the monthly sums. These values are then transferred to the irradiances on planes tilted equal to the latitude of the sites using the simple Liu/Jordan model (Liu and Jordan 1960).

3.2.2 Load data

As mentioned in section 2.3, no general applicable model for the generation of synthetic load data is available up to now. The information given by Vernetti and Kleinkauf (1999) is in its details much affected by the properties of the two systems analyzed. A direct use of this model would overstress its general applicability. We use here a more simplified heuristic way that tends describe the load conditions by few basic parameters.

For the following analysis of the performance of PV/Diesel systems without storage, which is limited to the daytime performance, the average daytime load is used as basis for the load data. This value is superimposed with fluctuations showing a time independent normal distribution with a standard deviation of 0.3 times the average daytime load. This value is chosen in approximate accordance with the information given by Vernetti and Kleinkauf (1999) for the load fluctuation in systems with a ratio of the peak load (~ nominal power of the DGS) to the daytime load in the range of 2-3. For simulating systems with a smaller ratio of the nominal DGS power to the average daytime load, the amplitude of the fluctuations is reduced to avoid unreasonable load values. In case of the presence of information on the average daily load pattern, the random fluctuations may be superimposed to this average daily evolution.

3.3 Identification of a general system characterization

For the analysis of the potential of a specific technology it seems reasonable to select a minimal set of parameters that seems to be appropriate to characterise the layout of the systems. For the simple PV diesel systems we have decided on two characteristic values. The first is the size of the PV generator, given by its nominal (STC) power relative to the average daytime load: $P_{stc}/P_{load(day)}$. The second is the rated power of the DGS given as multiple of the daytime load: $P_{nom}/P_{load(day)}$. This parameter has the dominating influence on the magnitude of the part load operation during daytime. Whereas the first parameter is the output of a process deciding on the PV share in the system, the second one characterises the existing installations.

4. SIMULATION RESULTS

In this section simulation calculations are used to get an overview on the useful PV production and the associated fuel savings. The results presented here refer to two locations in Brazil (Florianópolis and Fortaleza), which approximate the worst and the best radiation conditions in Brazil (see figure 2). Thus they give an indication of the range of results expected.

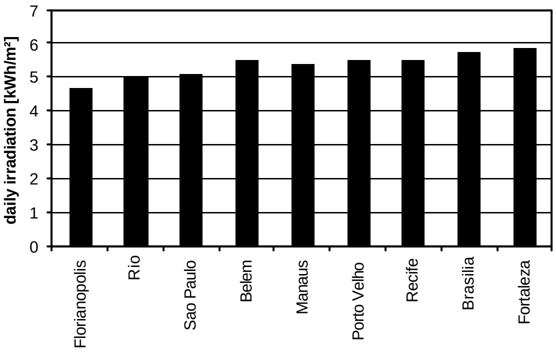

Fig. 2: Annual average daily radiation sums for various sites in Brazil. The Data are based on the Solar Radiation Atlas for Brazil [Colle and Pereira 1998]. For comparison: the annual average daily radiation sum for a typical site in Germany is about 2.6 kWh/m².

First, examples of the performance figures evaluated for a fixed value of the relative DGS size $P_{nom}/P_{load(day)}$ are presented. The values given in figure 3a for the fuel savings refer to a DGS with a $P_{nom}/P_{load(day)}$ value of 2. In this figure the effect of the reduction of the specific fuel saving potential with increasing size of the PV is remarkable.

The associated PV yield (here: useful energy production per installed PV power) is given in figure 3b. Obviously the yield shows the expected decrease due to the dumping of surplus PV energy.

The sensitivity of these results to the choice of the nominal capacity of the DGS is presented in figure 4. The increase of the diesel size from 2 to 3 times the average daytime load can reduce the fuel savings by about 1/3.

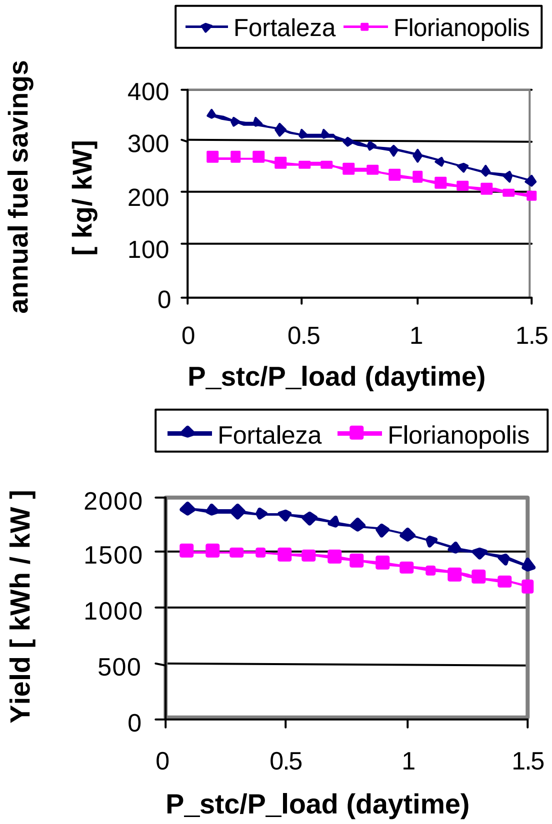

Fig. 3: Results of simulation runs for the specific fuel savings (3a, upper figure) and the yield (3b, lower figure) for PV generators in PV-Diesel Systems without storage as function of the size (STC-power) of the the PV generator, normalized by the average load during daytime. The meteorological conditions of Florianópolis and Fortaleza are used as input. The examples given refer to systems with a DGS with a nominal capacity of twice the average daytime load.

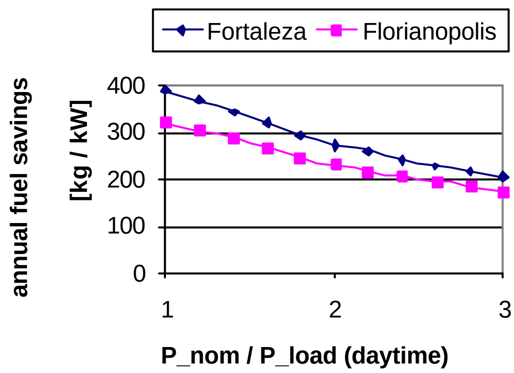

Fig. 4: Same presentation as figure 3a, but for a constant PV-size ($P_{stc}/P_{load\ (daytime)}$ = 1) and a variation of the nominal capacity of the DGS. Due to the requirement of a minimum load for the DGS (here 0.15 P_{nom}) the fuel savings are reduced remarkably by the increase of the nominal power.

The main contribution to this reduction is due to the associated increase of the minimum load level. As mentioned above, relieve from this problem – not discussed here - could be given by the application of several generator units to form the overall DGS capacities.

From these results we can conclude, that annual fuel savings of about 250 – 300 kg per kW of PV installed can be expected, depending on the location. Prerequists for these values are a PV rating close to the average daytime load and a DGS that is sized reasonably in relation to this load.

5. A CASE STUDY: THE OVERALL PERFORMANCE OF THE SYSTEM AT ARARAS, RONDONIA

5.1 General situation

The village of Araras is located in the state of Rondonia in the Brazilian Amazon (10^o 13' S; 65^o 21 W). As mentioned before the electricity supply in the settlements of this region - when it exists - is done via isolated mini-grids based on small to medium diesel or oil power stations. The production costs for a kWh of electricity are therefore higher than in the metropolitan areas. In view of guaranteeing equal life conditions to the people in this region, the government of Brazil – federal and regional - subsidises the electricity generation at these places. The subsidies are financed in part from the electricity rates for the consumers of the Brazilian interconnected grid.

5.2 *The PV/Diesel system at Araras*

The pre-existing system in Araras had three diesel generators sets, each one with 60 kVA (54 kW) nominal power installed. The diesels have been installed more than 10 years ago. Unfortunately no information on their actual part load behaviour is available.

This configuration was designed for an average load of about 50 kW. One diesel was supposed to run permanently, the second at peak time only. The third was a back up unit. To this configuration a PV generator with a nameplate rating of 21 kW was added in 2001. The actual system scheme is given in fig. 5.

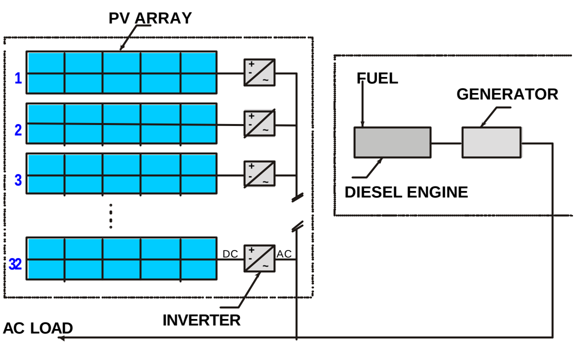

Figure 5: Schematic diagram of the Diesel / PV system without storage currently in operation at Araras, Rondonia (Rüther et al. 2000).

Since 2001 however, the consumption has been reduced drastically. The reason is a migration away from Araras due to a partial depletion of the local gold resources, which were a main income factor. The actual load characteristics will be discussed in the next sections, together with information on the performance of the PV system

5.3 Load conditions at Araras

Figure 6 shows an average load curve for the system at Araras. This pattern, dominated by a high share of cooling loads (refrigerators and freezers), is typical for the Amazon region. The ratio of maximum load (at the early evening hours) to the average load is lower than the typical values discussed in the literature cited above.

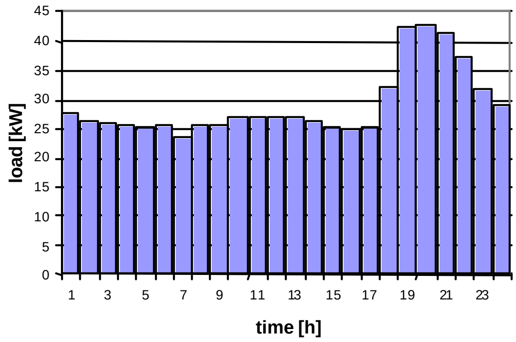

Figure 6: Average daily load curve of the Araras, RO grid (Rüther and Montenegro 2000) during July to September 2002. The average load is 27 kW (equivalent to about 650 kWh/day).

5.4 The performance of the Araras system

Using detailed data that had been taken from June to September 2002, the performance of the PV generator and the sharing of the load coverage between the DGS and the PV generator are analysed.

Figure 7 gives an example for the AC-performance of the PV-Generator (first week of July 2002).

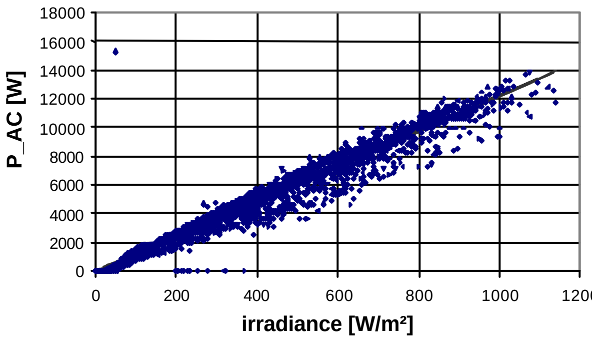

Fig. 7: AC-performance of the PV generator at Araras. The actual performance of the generator (nameplate rating 21 kW) is equivalent to a rating of about 12.5 kW.

It is obvious, that the AC Power output at an irradiance of 1000 W/m² is close to 12.5 kW only. This may be mainly traced back to problems in the operation of the 32 string inverters used in the system. Due to various reasons (overheating, conflicts for the inverters designed to operate under standard grid conditions to deal with the increased frequency variability of the local grid,….) the inverters show frequent downtimes. As the individual downtime periods of the inverters seem not to be correlated, the overall performance of the system can be well described by a linear response.

Bearing in mind that we are dealing with an unwanted down rating of the PV-generator, we take a value of 12.5 kW as 'effective rating' into account for the following considerations.

Figure 8 gives the distribution of the values for the daily gain of the PV generator [kWh/day] in the period inspected. The average gain is about 50 kWh/day. This presents a performance ratio of PR=0.5 with respect to the nameplate rating. With respect to the 'effective rating' this value is increased to 0.84.

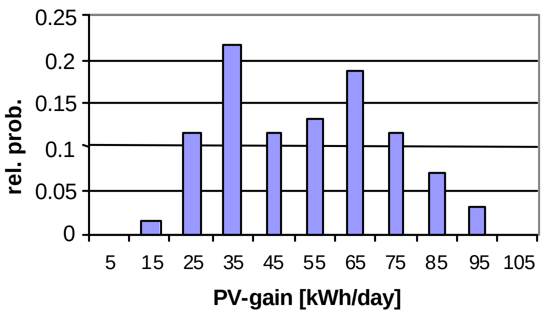

Fig. 8: Distribution of the daily energy gain of the PV-generator at Araras for the period inspected. Taking the effective rating of the PV generator (see text) these gains represent a performance ratio of 0.84.

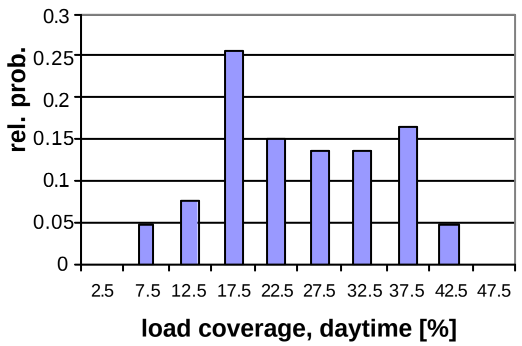

Fig. 9: Distribution of the daytime load coverage by PV in the Araras system. The average is at about 20%.

The contribution of PV to the load coverage during daytime is given in figure 9. The average value is about 20%. For the day and night total the load coverage is 8%. This value again reflects the almost equal contribution of daytime and night hours to the total load.

Using the annual integral of 18600 kWh for the PV production as reported by the system operator for the year 2002, the daily PV gain from the period inspected (50 kWh/day) is almost identical to the yearly average of the daily production (51 kWh/day). Also the figure for the annual load coverage of 8.3% is close to the value for the month inspected in detail. Again referring to the 'effective rating', the yield is 1488 kWh/kW. This value is somewhat lower than what could be expected from the simulation shown in figure 3 (According to the radiation atlas the annual average radiation sum at Araras is 5.4 kWh/day as compared to a value of 5.8 kWh/day for Fortaleza and about 4.5 kWh/day for Florianópolis).

From information on the monthly fuel consumption the fuel savings due to the PV generator may be assessed. Combining these data with the monthly electricity produced by the DGS, results in an average specific fuel consumption of the DGS of 0.40 kg/kWh. The ratio of the fuel consumption to the load of the grid covered is 0.37 kg/kWh. The difference of the last two figures indicates the benefits from the PV.

It should be noted that these values for the specific fuel consumption are much higher than those discussed in Chapter 2 (fig.1). The DGS at Araras is neither new nor can it be maintained or operated in view of an optimised efficiency. The non optimal fuel use in the DGS is however expected to increase the fuel savings by the PV.

To quantify the fuel savings, the fuel consumption necessary to cover the load by the DGS alone is estimated. For this purpose, the daily specific consumption of the DGS and the daily DGS production are analysed. Assuming a linear relation between these data, the fuel consumption for the coverage of the total load is determined. The results for the monthly consumptions, expressed as monthly averages of the daily sums are given in fig. 10. A system without PV would have had a fuel consumption value about 55% higher than the actual one, i.e. the PV leads to a 5.5% reduction of the fuel use. The deviation of this figure from the share of load coverage must be traced back to the fuel consumption characteristics of the DGS (which are in detail up to now unknown).

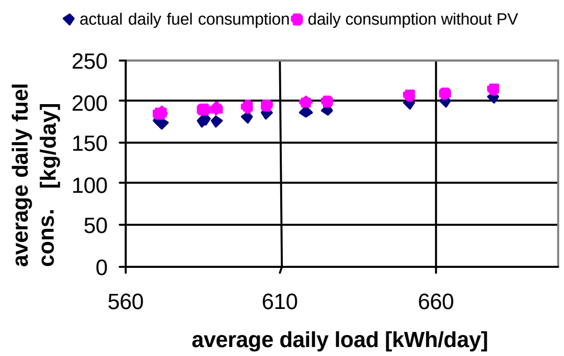

Fig.10: Monthly averages of the daily fuel consumption as given by measured data (diamonds) and estimated values (dots) for a system without PV. The PV gives a 5.5% reduction of the fuel consumption.

Integrating the fuel savings annually, a specific saving per installed PV capacity ('effective' value) of some 315 kg/kW can be identified. Due to these high savings which are caused by the reduced efficiency of the DGS as stated above, and despite the fact that the PV gain is - even using the reduced rating - somewhat below the expectations, this value shows good correspondence with the simulation results as given in figure 3.

6. ECONOMIC ASPECTS

Using the information on the expected fuel savings gained from both, the simulation runs and the system data, the economic feasibility of this type of PV application can be discussed. As prerequisite of this discussion, the organizational structure of the electricity supply in the Amazon region is represented here.

The DGS are operated by independent power producers (IPP). The IPP, as contractors to the state-owned utility, are responsible for the electricity supply at the remote locations. They charge the consumers with a kWh tariff fixed by the government. From this income, they have to carry the investment in the DGS and the operation and maintenance costs. The fuel itself is supplied by the utility to the IPP without charge, as long as the specific fuel consumption, measured in *l* per kWh, does not surpass an upper limit (currently 0.34 *l*/kWh). The utility has to carry all the associated costs, including transportation. The additional costs arising for the utilities that have to supply electricity in remote regions are leveled on a national scale. Due to this structure the integration of new technologies has the two actors - the IPP and the utility - who are operating under different economic conditions.

To make a basic assessment of the overall economic situation, we look at the benefits from the fuel saving first. The benefits, depending on to whom the PV belongs, may occur either for the utility or for the IPP, given the case that the utility transfers the savings due to reduced fuel costs.

Based on a value of 320 kg/kW for the fuel savings per installed PV capacity – which is at the upper margin of the expected savings, prices for PV of 4300 US$/kW (Rüther et al. 2000), the actual price of fuel at Araras (according to information from the utility: 0.47 US$/l), a 20 year lifetime and a discount rate of 6%, it is obvious, that the PV can not be economic based on the fuel savings alone. Taking these assumptions, only 48% of the investment would be returned. Because of their extremely remote situation in Rondonia the fuel price for some DGS goes up to 0.68 US$/*l*. But even in this case, only approximately 70% of the investment for the system would return. For a positive economy, a fuel price – with all other figures unchanged – of more than 0.95 US$/*l* is required. An increased discount rate of 12% rises the critical value for the fuel price to 1.36 US$/*l*. As it is unlikely that such high fuel prices will appear in the near future, it can thus be stated that even for this PV application, which appears quite effective concerning the fuel savings, additional incentives are necessary. The incentives have to guarantee for the return of a share of approximately 50% (as for the example of Araras) of the investment.

There are two main kinds of possible incentives: an incentive for the energy that is produced, e.g. in form of a rate based incentive, or a subsidy that is given for the power installation. Looking at the rate based incentive, a value of either 0.14 US$/kWh for the case of a discount rate of 6% or 0.28 US$/kWh at 12% are required. Due to social reasons this incentive has to be covered by public funding and has to be transferred to the owner of the system. Regarding the subsidy to the initial investment, a rate of 54% of the investment costs has to be donated in the case of a 6% interest rate and of 70% in the case of a 12% interest rate. Assuming an interest rate of 0% would reduce this share to 20%.

If one of these options for incentives can be realized, the market niche that is created could be remarkable. Taking into account the total capacity of DGS with a size below 100 kW in the Amazon region and applying the small penetration rates of PV that we have discussed here, a potential of about 3 MW of PV can be estimated (Rüther et al. 2003).

7. CONCLUSIONS

We have presented the option of implementing a limited share of PV-generation without storage into existing medium size mini-grids that today are powered by diesel generator sets. If the restrictions for the reasonable size of the PV in this application are obeyed, an annual saving of about 250–300 kg of fuel per kW of installed PV-capacity can be expected, given the meteorological conditions in Brazil. These numbers are based on the results of simulation calculations and the analysis of the performance of a pilot project in the Brazilian Amazon. For the exploitation of the high technical potential that exists for this type of PV application at remote locations in Northern Brazil, incentives are nevertheless still necessary. The incentives that are needed here are however modest when compared to those necessary in other markets.

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