TECHNICAL AND ECONOMIC ANALYSIS OF A PV/DIESEL HYBRID SYSTEM APPLIED TO RURAL ELECTRIFICATION FOR ISOLATED COMMUNITIES IN NORTHERN BRAZILIAN REGION

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Abstract — **A technical and economic feasibility analysis on a hybrid photovoltaic-diesel system is presented for a typical village located in the northern Brazilian rain forest region. A 24 kW photovoltaic system is proposed to be installed on a hybrid configuration with a 150 kVA existing diesel generator. Based on electricity demand profiles and current costs, the analysis shows a payback time which is still too long and not economically attractive without government subsidies. However, with the declining costs of photovoltaic technology predicted for the next few years and the continuously increasing costs of diesel, the hybrid photovoltaic-diesel systems may become economically viable, thus representing a huge potential in the near future. Real electricity demand profiles are also presented for several typical isolated communities located in that region.**

I. INTRODUCTION

Photovoltaic systems (PV systems) can be a reliable alternative to complement grid based power, which is often too costly for sparsely populated and remote areas. They have the advantage to use renewable energy and to present a very low operating and maintenance cost, in comparison to diesel engines or other fossil fuel alternatives. Additionally, as a non-aggressive technology, PV systems can be used also to minimize the CO_2 emission or any negative environmental impact caused by fuel engines. Numerous experiences around the world have confirmed the technical reliability of PV systems and their economic applicability in rural electrification programs [1].

In the northern Brazilian rain forest region there are many villages that are not connected to the national electricity grid. In these remote places, electrical energy is usually generated by diesel engines coupled to AC generators and these are connected to local isolated mini-grids. The typical nominal capacity of the diesel generator sets is well below 1 MVA. In many cases, these isolated communities can only be reached by boat or dirt roads, and diesel supply is therefore costly and unreliable. To reduce the impact of these high generation costs to the end-user, diesel is subsidized by the Brazilian government (through the National Fuel Consumption Account). Presently the government is planning to finance renewable energy projects, including undispatchable energy sources like wind and solar, to offset the cost burden and environmental consequences of diesel consumption. Considering the high levels of insolation available in these regions (typically above 2000 kWh/m^2/year on average), photovoltaic solar energy conversion, on a hybrid configuration with the diesel generator sets already in operation at these sites, is a potential candidate as a reliable, clean and renewable energy source. In this paper, a technical and economic feasibility analysis on a hybrid photovoltaic-diesel system to be installed in a small village located in the state of Acre (Brazil) is considered. Based on the electricity demand profiles of a typical village in that region, a 24kW photovoltaic system is proposed to be installed on a hybrid configuration with a 150kVA existing diesel generator. Based on current costs, the analysis shows a payback time which is still too long and not economically attractive without government subsidies. However, with the declining costs of photovoltaic technology predicted for the next few years, the continuously increasing costs of diesel and the end of the National Fuel Consumption Account in 2013, hybrid photovoltaic-diesel systems may become economically viable, thus representing a huge potential in the near future.

II. TECHNICAL DESIGN CONSIDERATIONS

The hybrid PV/diesel generator system comprises an already installed and operational diesel generator and a latest generation thin film PV array. The diesel genset includes a diesel engine, which is coupled to a synchronous generator that delivers AC electrical power at 220V and 60Hz (true sine-wave). The diesel genset is rated at 150 kVA and is responsible for baseload supply at all times in this installation. The PV array is an auxiliary energy source, designed to offset diesel consumption at high solar irradiance periods, and is rated at 24 kWp DC. The PV system is parallel connected to the diesel genset by means of DC-AC converters (inverters), which is synchronized by the diesel generator. To avoid the islanding effect, inverters were chosen which automatically disconnect the PV array in the case of grid failure or disconnection, to prevent the grid being energized unintentionally.

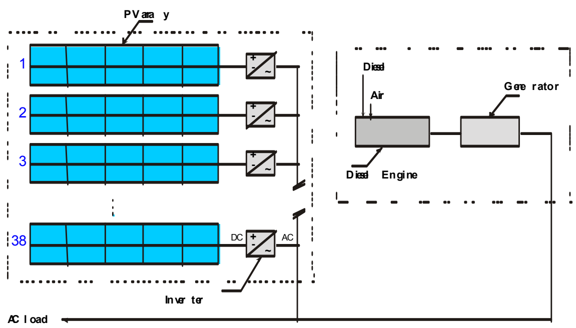

Figure 1- The proposed hybrid photovoltaic/diesel configuration.

Fig. 1 shows a schematic diagram of the hybrid installation. The PV system consists of 380 triple-junction thin film amorphous silicon US64 modules, each rated at 64 Wp, totaling 24320 Wp DC at Standard Testing Conditions (STC, irradiance = 1000 W/m^2; solar cell operating temperature = 25^{o}C; spectral content of sunlight = AM1.5). The PV array covers an area of some 300 m^2, with PV modules distributed in a parallel/series configuration of 190 two-module strings connected to 38 line-commutated sine-wave inverters. Each inverter is connected to five strings of two modules each, resulting in a 640W @ 33VDC input. Instead of using one single inverter rated at the total PV system power rating, this 38 lower-power inverter configuration was chosen, in order to reduce the risk of total system downtime due to inverter failure. Furthermore, in case one inverter fails, the PV modules connected to that inverter can be reassigned and distributed among the remaining inverters, since each inverter is slightly overrated with respect to the total input power assigned to it in the present design. This will also allow for operation closer to the inverter's efficiency maximum, which lies well bellow its maximum continuous rating (for DC inputs over 100W we have routinely measured inverter efficiencies over 90% for this inverter model [2]. For increased power yield when partly shadowed and also to minimize module mismatch losses, the system configuration uses parallel connection of all two-module strings. With parallel connection the power losses related to string diodes usually found in large series-connected PV module strings are also avoided. Furthermore, the low voltage (33VDC) and low power (128W) of the individual strings on the DC side of the system are considered safe installation conditions to the untrained individuals involved. Contrary to other PV systems reported in the literature [3] and [4], where the inverter system is undersized in comparison with the PV system's rated power, our inverters are overrated as previously mentioned. For irradiance levels over 250 W/m^2, inverter efficiencies over 90% are reached, which guarantees operation close to the inverters' maximum efficiency level most of the time. For a typical clear day we have previously observed that only less than 5% of the incoming energy is in the less than 250 W/m^2 range [2]. With overrating we also avoid the energy losses caused by overloading the inverter under maximum irradiance conditions, which form a significant portion of daylight hours at the site. In vertical-mounting and high latitude-installed PV systems this is usually not the case, justifying the option for inverter undersizing typical of most European installations.

Most hybrid PV/diesel systems described in the literature [1], [5] and [6] use battery storage, which represents additional installation costs and maintenance, as well as the inconvenience and extra costs of periodic replacement due to the batteries reduced lifetime. In this respect the present design offers a more energy-efficient approach since batteries are not used and the PV system is feeding in real time to the mini-grid all the power produced.

Diesel genset performance data, real electricity demand profiles and solar radiation data are available for typical isolated communities in the Brazilian rain forest. Three small villages located in the state of Acre (Porto Walter, Thaumaturgo and Santa Rosa) have been first considered as candidates for using an hybrid system. In this paper the economic analysis is focused on the Santa Rosa power plant. All three villages are located close to the Bolivian and Peruvian borders. There is no connection by road. The diesel transporting is made by ship along existing rivers. Sometimes the access to the site is possible only by small planes. The electricity is generated by a set of diesel engines coupled to AC generators. Usually, an additional diesel generator is provided as a backup unit, for preventing power shortages in the event of generator breakdown. The diesel system is then connected to a local mini-grid to serve the respective village during 24 hours per day.

Fig. 2 shows the electricity demand profiles along an entire day for the selected villages. According to Figure 2, one sees that the power consumption behavior is almost the same for all villages. In the case of Santa Rosa, the average power consumption is about 30 kW, with a peak between 17 and 22 hours. The total measured electricity power generation is 280 MWh/year.

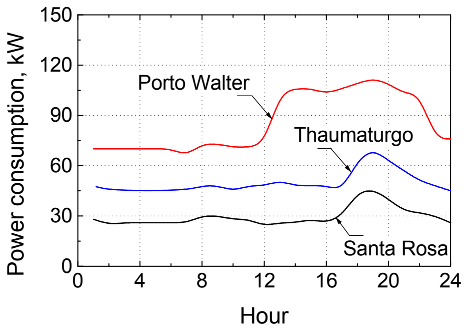

Figure 2- Electricity demand profiles along a whole day, for some villages in Acre.

The diesel genset performance data are also required in the analysis. As reported by Bazzo et al [7], the specific consumption of the diesel systems were measured to be in the range of 0.34 to 0.36 l/kWh. The main characteristics of the target diesel systems located in Santa Rosa, Thaumaturgo and Porto Walter are shown in Table 1. Further data regarding the capacity of diesel systems installed in the Brazilian rain forest are shown in Table 2 [7] and [8]. The data in Table 2 regarding the sates of Amazon, Para, Amapá, Roraima e Fernando de Noronha were obtained from ANEEL, the Brazilian Electricity Regulatory Agency.

Insolation data for the region are shown in Fig. 3, which presents the daily insolation (monthly means) in kWh/m^2/day [9].

Table 1- Main characteristics of the target diesel systems located in the state of Acre.

Village	Location	Installed Power (kW)	Specific Consumption (l/kWh)	Demand (MWh/year)	Specific O&M cost (US$/MWh)
Santa Rosa	S 9^{0}26'' W 70^{0}29'	150	0.36	280	190
Thaumaturgo	S 8^{0}57'' W 72^{0}47'	350	0.36	286	214
Porto Walter	S 8^{0}16'' W 72^{0}45'	480	0.34	483	154

Table 2- Nominal capacity of diesel systems installed in the Brazilian rain forest (Only isolated diesel engines).

State	**Installed Power (kW)**	Number of Diesel Power Plants	Number of Power Plants < 1 MW
Acre	29224	16	9
Rondonia	96795	56	43
Amazon	149824	86	32
Pará	89691	46	28
Amapá	15655	7	5
Roraima	12031	69	67
F.Noronha	2314	1	-

Source: Brazilian Electricity Regulatory Agency (ANEEL), 1999.

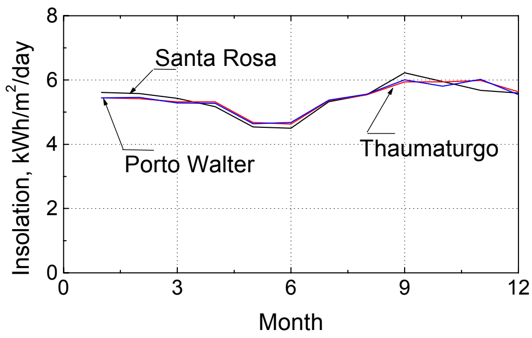

Figure 3- Average daily insolation measured along every month for Thaumaturgo, Porto Walter and Santa Rosa villages.

III. ECONOMIC ANALYSIS

To evaluate potential investments an economic analysis is made taking into account the initial cost, the annual operating and maintenance costs, annual interest, depreciation and salvage value. The discounted payback period and the internal rate of return (IRR) are considered in this analysis. The evaluation thus takes into account the time value of money and all cash flow streams during the life of the project. Federal income and import taxes are not considered.

The initial investment cost required to install a 24 kWp photovoltaic system is assumed to be around 4.2 US$/Wp.

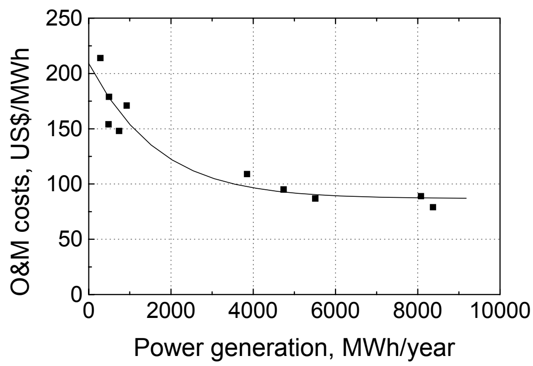

Figure 4- Annual O&M costs, based on 10 small isolated diesel system power plants (Acre-Brazil).

The annual operating and maintenance costs are shown in Fig. 4. For the Santa Rosa power plant, as the total power consumption along one year is 280 MWh, the corresponding O&M costs are 190 US$/MWh. It is expected only a slight reduction in the O&M costs, once the expenses with personnel, lubricating oil and preventive maintenance will continue the same. Because of the importance that fuel costs play in thermal systems, generating fuel costs are considered separately from O&M costs in this work. The continuously increasing cost of diesel, as planned by the Brazilian government for the next years, with the phasing out of the National Fuel

Consumption Account, is considered in the economic analysis. In this work, it is anticipated an average annual increasing rate of 5%.

In order to make the investment more economically attractive, a sensitive analysis is performed considering government subsidies and possible future environmental taxes. Taking into account only 50% of the installed power of all isolated diesel systems in the Brazilian rain forest (see Table 2), the total CO_2 emission can amount to 1.5 10^6 tonCO_2/year. In case of Santa Rosa power plant, the total CO_2 emission amounts to 252 tonCO_2/ year. The corresponding reduction amounts to 39 tonCO_2/ year (15%). The reduction of CO_2 emission is estimated taking into account the displace of diesel by using the solar energy. Other greenhouse gas (GHG) emissions are not considered. Environmental taxes from 0 to 120 US$/ton$CO_2$/year are considered just for analysis.

The salvage values are calculated along the lifetime of the power plant for three scenarios:

Scenario 1: Fixed diesel cost.

Scenario 2: Increasing diesel cost of 5% per year.

Scenario 3: Increasing diesel cost of 5% and environmental taxes up to 120 US$/ton$CO_2$ per year.

The following assumptions are also made in the analysis: Interest rate: 6% and borrowed capital: 50%;

Fig. 5 and Fig. 6 show the payback period required to recover the initial investment and the internal rate of return (IRR) related to scenarios 1 and 2, respectively, taking into account government subsidies from 0 to 100% of the initial investment. The economic viability of the hybrid system is strongly dependent of government subsidies. For scenario 1, the project is attractive only for government subsidies greater than 45% (Payback<22 years; IRR>12%). For scenario 2, the project is attractive for government subsidies greater than 15% (Payback<23 years; IRR>12%).

Fig. 7 and Fig. 8 show the payback period required to recover the initial investment and the internal rate of return related to scenario 3. It is clear the strong influence of the environmental taxes on the investment. In this case no government subsidies are required, unless the environmental taxes are fixed below 40 US$/ton$CO_2$ per year.

Diesel gensets usually have their lowest generation costs when operating at over 50% of their nominal capacity. The installations described in this work are operating at under 30 % of their rated capacity. The economic analysis could thus be more favorable for installations with a better match between installed and operating capacity.

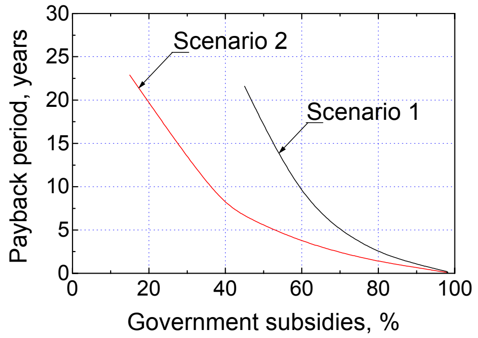

Figure 5- Payback period required to recover the initial investment (Scenarios 1 and 2).

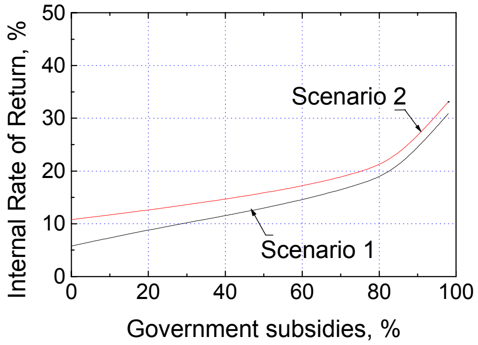

Figure 6- Internal rate of return of the investment (Scenarios 1 and 2).

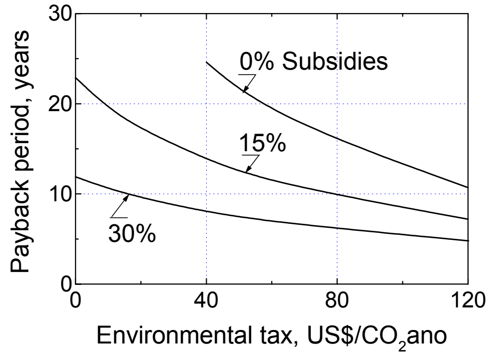

Figure 7- Payback period required for Scenario 3, taking government subsidies of 0, 15 and 30%.

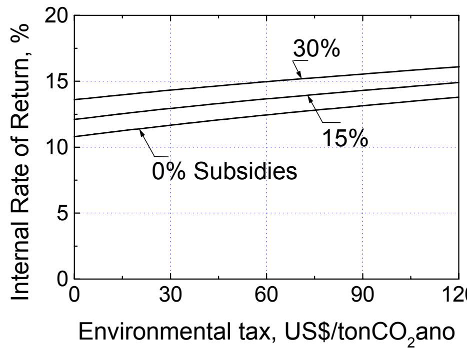

Figure 8- Internal rate of return for Scenario 3, taking government subsidies of 0, 15 and 30%.

IV. CONCLUSION

A 24 kWp PV system is proposed to be installed as a hybrid PV/diesel system for testing in Santa Rosa, a typical village located in the Brazilian rain forest. The economic viability of such a hybrid system is still strongly dependent of government subsidies. However, taking into account a continuously increasing cost of diesel, as planned by the Brazilian government for the next years, and considering environmental taxes as proposed by international environmental commitments, such as the Kyoto Protocol, hybrid systems can become economically attractive. There is a strong influence of environmental taxes on the economic viability of the hybrid systems, as shown in the analysis. For environmental taxes fixed above 40 US$/ton$CO_2$ per year and taking into account current diesel prices in the Brazilian market, there is no need of any government subsidies to install hybrid photovoltaic/diesel systems to attend isolated communities in the Brazilian rain forest.

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