Optimization of a Hybrid Energy System for an Isolated Community in Brazil

Tiago Targino Sepulveda*‡, Luciana Martinez*

*Department of Electrical Engineering, Federal University of Bahia, Salvador, Brazil

(tiagots_@hotmail.com, lucianam@ufba.br)

‡ Corresponding Author; Tiago Targino Sepulveda, Federal University of Bahia, tiagots_@hotmail.com

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Abstract- Undeniably the basic needs of a man are numerous. A traditional list includes food, shelter and clothing. However, for a contemporary man, the lack of access to electricity is strongly connected to the social exclusion. In Brazil, isolate villages is still a reality because the costs to expand the national grid can be unattractive. An alternative solution is to design an off-grid power system, normally using a diesel generator. This paper investigates the costs of a micro-grid developed for an isolate community located in amazon region. Their costs can be minimized if the best combination of hybrid energy systems is applied. The micro-grid has been optimized using HOMER (Hybrid Optimization Model for Electric Renewables) software. Results show the Cost of Energy (COE) for different demands and the costs associated to operation. Considering the daily radiation and average wind speed of the site, it was found the substitution of wind turbines by adding more photovoltaic panels with a diesel generator and batteries. Annual dispends can be reduced 54% when the optimal configuration is applied.

Keywords Optimization, Renewable Resources, Hybrid System, Isolated System, HOMER.

1. Introduction

According to the last census produced by the Instituto Brasileiro de Geografia e Estatística IBGE (Brazil Institute of Geography and Statistics) it is estimate that 2.7 million Brazilians do not have access to electricity. This issue is more evidenced on the countryside, specifically on the northern, where 1 in 4 residences are private of the service of electricity [1]. Furthermore, there are thousands of communities that are not connected to the national electricity grid. That occurs because the connection through network extension is neither economically nor technically viable. In those places energy is supply by different configurations. The most common is a diesel engine coupled to AC generators, and these are connected to local isolated mini grid [2]. Besides the government gives subsidies for purchasing fossil fuel, usually diesel, the power supply is highly costly and also involves environmental risks [3].

On the other hand, Brazil is a powerful producer of renewable energy. That happens because of its size, geographical localization and relief. In 2012 the country produced 75% of its electricity from renewable resources, most of the energy came from hydroelectricity. The Plano Decenal de Expansão de Energia PDEE (Ten Year Energy Expansion Plans) aims to raise the renewable participation to 86.1% of the electricity generation matrix by 2023. To accomplish this, one of the targets is to increase the capacity of wind power by 20GW [4].

The annual average sum of daily horizontal global solar irradiation in any Brazilian region is 1500-2500 kWh/m².The lowest value of irradiation in Brazil is greater or closer than the best scenario of some European countries, for example, Germany (900-1200 kWh/m²), France (900-1650kWh/m²) and Spain (1200-1850 kWh/m²). All these countries have projects to encouraging the use of photovoltaic solar power. The maximum values, more than 6.5 kWh/m²/day, are found in the semi-arid of Brazilian northeast, while the minimum values, 4.25 kWh/m²/day, occur in the coastal area of the Southern region [5].

Because of this promising scenario, Photovoltaic (PV) systems are now a trend in Brazil. It is now a profitable investment to realize for individual homes, especially after some incentives given by some states (São Paulo, Pernambuco, Goiás and Bahia) through the normative resolution 482/2012 [6]. The resolution provides the exemption of Imposto Sobre Circulação de Mercadorias e Serviços ICMS (Merchandise and Services Circulation Tax) for consumers who supply energy produced though micro and mini generation (capacity until 100MW) to the grid. The ICMS exemption reduces the pay-back time investment in solar panels in those states of Brazil.

Knowing the potential of renewable resources of Brazil and to solve the issue of lack of energy in isolated communities, the implementation of hybrid systems using renewable energy started to be implemented. The first hybrid off-grid system installed in Brazil has been operating since 1986. It is located in the island of Fernando de Noronha [7]. [8] presents an evaluation of different operation strategies of photovoltaic wind-diesel hybrid power systems at Cardoso Island located on the south coast of the state of São Paulo. The fundamentals of hybrid power systems and a hybrid system sizing technique are presented. [9] shows a hybrid PV-wind-diesel system generation located in the Amazon Region giving details of load curve and system components. They also exhibit an application of the first pre-payment system in Brazil installed in an isolated community.

The purpose of this paper is to find the best combination of hybrid system components to supply an isolated community. To accomplish this, a real case described in literature will be examined and simulated then it will be verified what is the optimal configuration for that particular case. In the results will be compared the Operation Cost, the Cost of Energy (COE) and the Total Net Present Cost (TNPC) for different demands.

The paper is structured as follows. Section 2 describes the software used to optimize the system. Section 3 defines the load data and meteorological conditions for the village chosen. Section 4 enumerates the components used for simulation. Section 5 presents the analysis findings and the results. Finally, section 6 presents the conclusion about the study realized.

2. HOMER Software

The Hybrid Optimization Model for Electric Renewables (HOMER) was chosen to simulate this study. It was developed by the National Renewable Energy Laboratory of the United States Department of Energy and it is available for free online [10]. It was developed to optimize the configuration of decentralized systems analysing all the alternatives looking for the optimal solution. The software HOMER simulates the operation of the system, calculating the energetic balance for each hour of the 8760 hours in a year. For each hour, HOMER compares the demand of energy and the capacity of the system to deliver energy at that time, determining how the generators operate and also the discharge of batteries [11]. Furthermore, the software calculates the total costs of fuels, the reposition of equipment, operation and maintenance. As a result, HOMER gives a list sorted by the best configurations for the system based on the TNPC and COE.

Many hybrid system sizing have been studied and optimized in literature using the software HOMER. [12] optimized a hybrid energy system model for electrification of a remote village in India. The lowest COE was observed in a Hydro-Diesel Generator system, however, a solar-wind-hydro-Diesel Generator can also be a viable option. [13] used HOMER for designed a renewable system considering energy efficiency and investigated the impact of increasing load profiles to the system. [14] discussed and designed a PV system to supply lighting load for a laboratory in Oman. The paper compared the results with a diesel generator system and concludes that the PV system is an economical option in Oman.

In [15], the authors propose the best hybrid technology combination of electricity generation to satisfy the electrical load of an off-grid remote village in India. It is considered a small-scale hydropower, solar PV systems, wind turbines and bio-diesel generators. The optimal was found combining a small hydropower, solar PV, a bio-diesel generator and batteries. Wind turbines tend to be very costly and it highly depends to the capacity factor of the place. In this village case, the wind capacity factor is low (average wind speed 3,5m/s). [16] presents a substitution of existing diesel power plants in isolated villages in Saudi Arabia. The paper analyses the viability of PV, batteries and diesel generators. It was found that a PV array and four generators operating at a load factor of 70% give the optimal COE.

3. Case Study and Data Description

In this paper, an isolated community (São Tomé village) located in Amazon Region was selected for the study. São Tomé Village is being supplied by electric power through a hybrid PV-wind-diesel system generation. The characterization of the community (location, load data) and the description of the hybrid system are given in details in [17].

The load data of the village (Fig.1) is a typical load daily consumption of an isolated village. The demand is usually low and has an increase during the nightfall. The peak demand is verified between 6pm and 7pm. The average daily load demand is 50.9 kWh/d, with a peak power equals to 4.60 kW. In September 2003 the operation of the hybrid system has begun.

The system is composed by PV-wind-diesel generators. The storage of the electric power generated by the renewable resources is realized by an association of batteries. When the batteries are discharged and the renewable sources do not attend the demand a diesel-electric backup generation is activated. The main data of the system are presented in Table 1. [17].

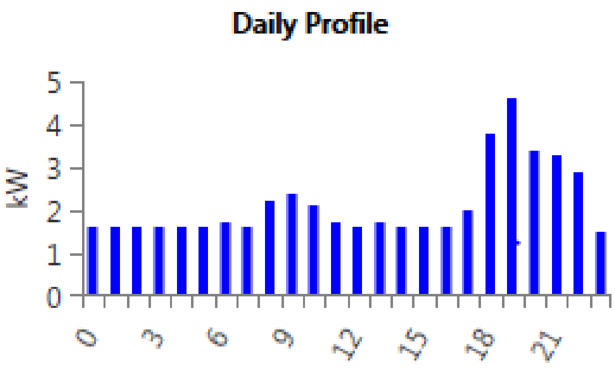

Fig. 1. Hourly Load Curve of São Tomé Village

The meteorological monthly data of solar insolation (Fig.2) and wind speed (Fig.3) for correspondent coordinates of São Tomé village (0°44'24"S and 47º28'59"W) are imported from the NASA metrological website [18]. The average daily radiation of the location is 5.33 kWh/m²/day while the annual average wind speed is 3.81 m/s.

Table 1. System components

Element	Size installed
PV modules	3.2 kW (80Wp each one)
Turbine Wind	7,5kW
Storage batteries	40 units (12V / 150 Ah each one)
Inverter	15kW (120Vdc/220Vac)
Diesel Generator	20 kVA

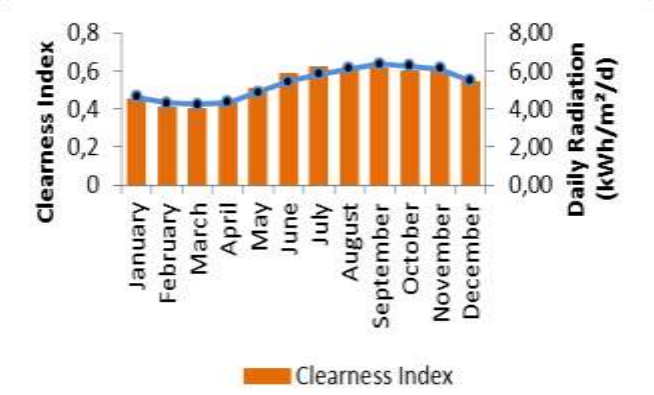

Fig. 2. Monthly data of solar insolation.

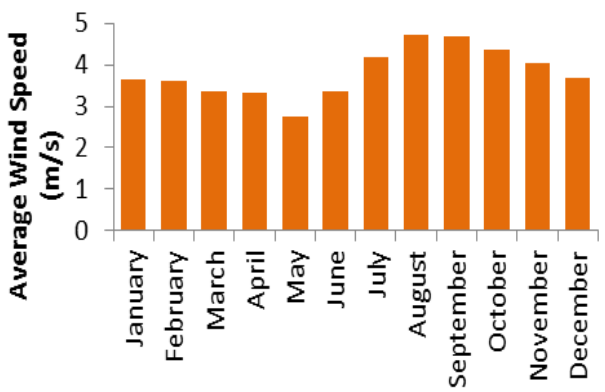

Fig. 3. Monthly average wind speed

4. System Components

Table 2. shows the costs associated to the common components of a hybrid system. Those values will be used to simulate the current system applied in São Tomé and to find the optimized system. The initial costs are based on the values found in Brazil's market. The following operation and maintenance costs are considered: 1% of initial cost of PV's system [19]; 2% of initial cost of wind system [20]. Costs of Operation and maintenance (O&M) are more significant in Diesel Generators compared to renewable systems. That happens because the cost of fuel is categorized as operational costs. The "Real" (R$) is the present-day currency of Brazil. The exchange rate for May 2016 is $1 = R$ 3.52 [21].

4.1 Solar system

Polycrystalline solar PV panels from Yingli Solar YL-250P are connected in series. They have maximum power 250W and short circuit current of 8.92A. The de-rating factor considered is 90% for each panel. They have no tracking system and the temperature effects are not considered. The Panels have efficiency of 15.4%. At the maximum power point the voltage and current are 29.8V and 6.71A correspondingly. The area of surface of each panel is 6.5m²

4.2 Wind system

A 7.5kW WindSpot, 6.3m rotor diameter, 3 Blade Upwind made by Polyester, wind turbine is considered. The hub height considered is 30m. It is the same hub height implemented by the original project described in [17].The generator is synchronous, permanent magnets, 3 phases, 48-110-220V at 50/60Hz. Characteristics of power output suggested by HOMER are given in Fig. 4.The start-up wind speed and cut-in wind speed are 3.4m/s and 3.0m/s respectively. Rated power output, 7.5kW, is given at 12m/s. Considering the average wind speed of the site (3.81m/s) the typical production of energy is 24kWh per day.

Table2. Costs of the components

Element	Initial cost (R$/kW)	Replacement Cost (R$/kW)	O&M (R$/year)	Life time (years)
Solar System	4,276	3,848	42.76	25
Wind Turbine	26,250	23,625	525.00	20
Battery	1,239 (per unit)	1,239	10.00	2
Rectifier / Inverter	2,204	2,204	0.00	10
Diesel Generator	1,226	1,226	0.03 (per hour)+fuel	15000 (hours)

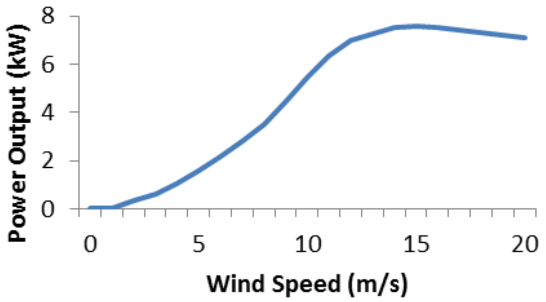

Fig. 4. Power Output – Wind turbine

4.3 Diesel Generator

The annual cost of diesel is based on the fuel curve (Fig. 5) suggested by HOMER. The fuel curve describes the amount of fuel which the generator consumes to produce electricity. The diesel fuel prices considered were: R$/L 0,80 and R$/L 3,10. The first cost of Diesel (R$/L 0,80) is the price of diesel subsided by the government through the Conta de Consumo de Combustíveis CCC (Account for Fuel Consumption). The subsidy reduces the cost of fuel to 26% of the normal cost for isolate systems that use diesel [17].

4.4 Batteries

Lead acid batteries were chosen, which–have nominal voltage of 12V and nominal capacity of 3kWh. The batteries are used to remains the voltage stable during peaks or discharge when the renewable generation capacity decreases. The capacity curve by discharge current of the battery is shown in Fig. 7 [22]. The maximum capacity of each battery is 227,42Ah and capacity ratio 0.39.

4.5 Converter System

. The efficiency of the converter system is 90%.The output voltage are 120VAC /240 VAC (invert mode) or 12-32 VDC (charge mode). The corresponding input current (charge mode) is 13A. Figure 6 shows a schematic of the connection between the AC bus and the DC bus.

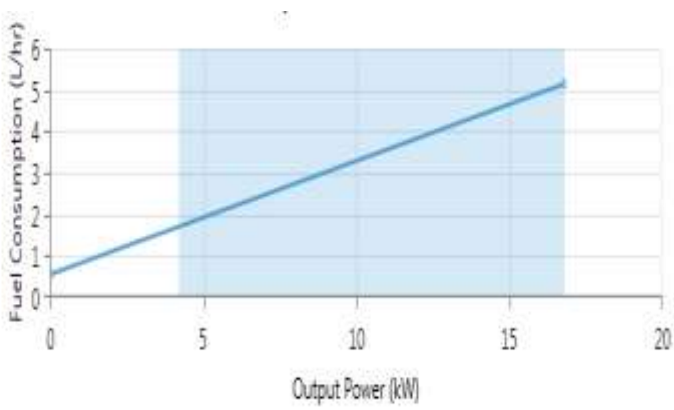

Fig. 5. Fuel Consumption vs. Output Power

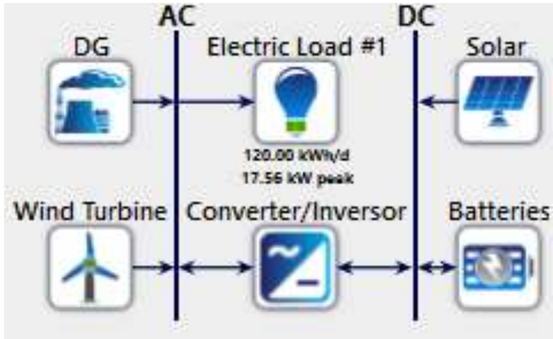

Fig. 6. Schematic

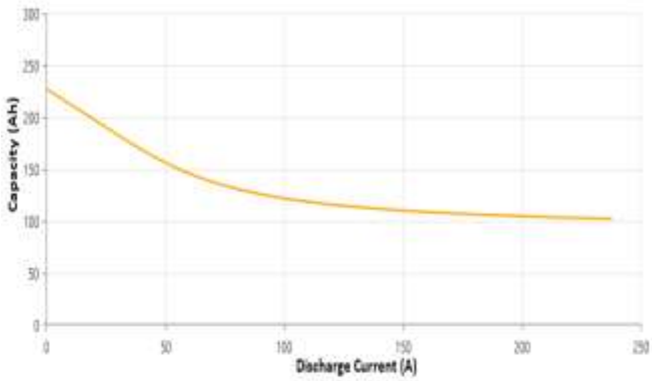

Fig. 7. Batteries Capacity Curve

5. Results

5.1 Original System

The sizes and prices of the elements simulated were mentioned on Table 1. And Table. 2 respectively. The values obtained for the price of kWh in R$ are shown on Table 3., where D is the demand in kW and IR is the interest rate.

The average demand of São Tomé village is around 2kW. Therefore, the cost of energy is equal to R$ 3.89/kWh (interest rate 10% / without CCC), which corresponds to an annual dispend of R$ 68,152 for 24h operation. If the CCC subside is considered the COE reduces to R$ 3.56/kWh and the annual dispend is reduced to R$ 62,371. The cost of generation can be substantially decreased when the demand of the village increases.

5.2 Optimized system

After running HOMER, the optimal sizing was found and it is shown in Table 4. Project lifetime, Interest Rates and diesel fuel prices are the same considered in the previous case. The optimization revels that it is more economical for São Tomé the investment in PV modules than a Turbine Wind, a similar result found by [14] in India.

Table 3. Cost of Energy – Original System

D (kW)	With CCC		Without CCC	
	IR 10%	IR 15%	IR 10%	IR 15%
1	6.83	8.25	6.83	8.25
2	3.56	4.25	3.89	4.58
3	2.53	2.99	3.07	3.52
4	2.02	2.36	2.66	3.01
5	1.69	1.96	2.31	2.58
6	1.46	1.69	2.12	2.35
7	1.31	1.50	1.98	2.18

Table 4. Optimized System

Element	Size Suggested
PV modules	18kW (250Wp each one)
Turbine Wind	0
Storage batteries	10 units (12V / 220 Ah each one)
Inverter	8kW (120Vdc/220Vac)
Diesel Generator	21 kVA

Table 5. shows the COE for different demands, considering interest rates at 10% and 15 %. Taking the same example, when the average demand is equal to 2kW, the cost of generation is equal to R$1.79/kWh (IR 10% / without CCC). The equivalent annual dispend is R$ 31,360 without CCC and R$ 24,177 with CCC. The percentage annual dispend reduction compared to the original system are 54% and 61% respectively. Similarly to the original system, when the demand increases the COE decreases considerably reaching the value of R$ 1.24/kWh or $0.35/kWh when the average demand is 7kW (IR 10%/without CCC).Table 6. shows the operation costs, fuel consumed and the Total Net Present Cost considering Interest Rates 10% and Diesel Fuel Price R$3,10. When the optimal solution is applied, as the demand increases the fuel consumed by the diesel generator decreases compared to the original system. Therefore, the operation cost reduces as well. It confirms the efficacy of optimization in reduces costs.

Table 5. Cost of Energy – Optimized System

D (kW)	With CCC		Without CCC	
	IR 10%	IR 15%	IR 10%	IR 15%
1	2.24	2.84	2.31	2.90
2	1.38	1.66	1.79	2.07
3	1.08	1.27	1.57	1.75
4	0.92	1.06	1.44	1.58
5	0.81	0.92	1.34	1.46
6	0.71	0.80	1.29	1.38
7	0.66	0.74	1.24	1.32

6. Conclusion

This paper presented the use of HOMER for optimizing a hybrid power system designed for an isolate village. The objective was reducing the cost of energy and costs of operation. Considering the load profile for different demands and the climate conditions of the village it was found that the least cost of energy and costs of operation were observed with a PV-DG-Batteries configuration. Annual dispends can be reduced 54% using the optimal configuration which makes the village less dependent of subsides. For reliability issues the diesel generator is still necessary. Even so, results show the reduction of fuel consumed for demands higher than 2kW.The high cost and low capacity factor makes the wind turbines not interesting for the village. Cost of energy can be minimized until R$1,24/kWh or $0,35kWh when the demand of the village increases which makes the project affordable considering that the access to electricity provides better quality of life and opportunities.

Table6. Summarized Comparative Results

D	OPERATION COST		FUEL CONSUMED (L)		NET PRESENT COST	
	Original	Optimized	Original	Optimized	Original	Optimized
1,0	R$ 28,286.00	R$ 7,478.00	5	259	R$ 594,770.00	R$ 200,928.00
2,0	R$ 36,510.00	R$ 18,522.00	2515	3202	R$ 676,467.00	R$ 310,941.00
3,0	R$ 48,977.00	R$ 28,447.00	6171	5728	R$ 800,312.00	R$ 409,234.00
4,0	R$ 61,707.00	R$ 37,681.00	9867	8154	R$ 926,771.00	R$ 500,958.00
5,0	R$ 69,560.00	R$ 46,049.00	12320	10464	R$ 1.004,775.00	R$ 584,086.00
6,0	R$ 79,878.00	R$ 55,013.00	15356	13609	R$ 1.107,279.00	R$ 673,139.00
7,0	R$ 89,888.00	R$ 63,496.00	18284	16077	R$ 1.206,718.00	R$ 757,408.00

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