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Analysis of Hybrid Solar/Wind/Diesel Renewable Energy System for off-grid Rural Electrification

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Abstract- Due to the rising energy demand and even the lack of coverage of the supplied energy to the total population from the interconnected electric system, the implementation of an electric generation system in which the renewables are involved plays an important role in our society. Furthermore, these energy systems help reduce the emissions of greenhouse gases to the environment and decrease their impact on climate change. However, there are certain limitations that justify the use of a diesel generator in these systems, such as: i) to backup electricity during peak hours; ii) to support the systems in periods with low levels of solar radiation and wind speeds; and iii) to reduce the cost of electricity (COE) of the system. The aim of this paper is to propose the design of a Hybrid Electric System (HES) to supply the energy demand of a rural parish placed on the Ecuadorian coast. The feasibility analysis, constitutive elements of the system, and adjust variables are computed and presented using the computational tool HOMER. This study is carried out considering the meteorological data obtained from the selected place, and two different prices for the diesel, i.e., subsidized and non-subsidized by the state, are considered. Additionally, technical and economic details of the proposed HES are presented.

Keywords Hybrid Electric System; HOMER; Renewable Energies, Feasibility Analysis.

1. Introduction

During the last years, the Off-Grid Power Systems (O-GPS) implementation supplied from different Renewable Energy Sources (RES) have been increasing, in spite of these sources are usually intermittent [1, 2]. The deployment of electrical systems is being carried out in both developed and developing countries [3 – 5]. It is due to several factors such as the downward trend in the cost of photovoltaic, wind systems and micro-hydraulic, as well as better technology and falling prices in electrical storage systems such as batteries. Therefore, there is a promising horizon for the implementation of these electrical systems in both residential and industrial users [6].

On the other hand, there are about 1.16 million people in developing countries without access to electricity [6], it is mainly due to its remote geographical location. Hence, with the mentioned scenario, O-GPS turns into a viable solution for supplying electrical energy to these areas of difficult access to the electricity grid.

In Ecuador, according to a study in [7], it was concluded that electricity coverage in rural areas is about 85%. According to a study in 2014, the provinces with the lowest electricity coverage are Napo, Pastaza and Santa Elena with a coverage of 86.97%, 87.58% and 90.81%, respectively [8].

According to a statistic government report in 2014, the generation of electricity in Ecuador coming from solar and wind resource, considering the total energy supplied, are about 0.07% and 0.32%, respectively [8]. Considering the geographic location of the country, there have been several efforts to start the efficient exploitation of these resources during the last years. For example, for power generation purposes, the Solar and Wind Atlas were published in 2008 and 2013, respectively [9].

Based on this information, Atahualpa parish placed in the Province of Santa Elena is chosen to study and analyze the feasibility of implementing O-GPS. This paper refers to the research project coded as ULVR-14-34, which corresponds to multi-stage works published in the form of preliminary results showing the solar and wind potential in selected parishes [10]; estimation of the residential electrical load profile of the families living in Atahualpa after the application of an in-situ survey [11], and finally, the analysis and propose of an off-grid electrical system solar-wind with 100% renewable sources [12].

This work continues with the feasibility analysis of these off-grid electrical systems, but now considering the hybrid type, i.e., a diesel generator takes part of the system. For this purpose, the authors have considered, similar to the study developed in [12]: the system costs, maintenances, subsidies, benefits, among others. Also, the electrical system was designed, simulated and optimized using the HOMER software tool, a program developed by the National Renewable Energy Laboratory in the United States [13] [14].

The rest of the paper is divided as follows: Section 2 is mainly dedicated to general information about the process for the modeled system and characteristics of the selected place. Section 3 presents the system specification based on the computational tool used. Simulation results and discussions are given in Section 4. Finally, the conclusions of the present study are presented in Section 5.

2. Methodology

Similar to the steps considered in [12]: geographic and demographic information site, estimated load profile, assessment of RES potential and modeling with variable sensitivity, are briefly described. It should be noted that these data are used for the performance of simulations and optimizations in HOMER. Figure 1 shows the sequence of the steps followed during the research.

2.1. Location and population

This study is performed in Atahualpa parish, Province of Santa Elena, one of the provinces between the lowest coverage of electricity distribution of the country. Geographically, it is located in the Ecuadorian coast in the coordinates 2º19' S latitude and 80º46' W longitude. It is 47 meters above sea level, it has a population of approximately 3600 people and 812 homes. Unsatisfactory basic services has been determined in 75.6%. The climate is considered arid, and there are two seasons, wet and dry. The maximum precipitation value is 150 mm, and temperatures ranging between 21 and 40 °C [10-12].

2.2. Electric load profiles

In studies of this kind, the estimation of energy demand is an important part of the energy analysis. The estimation of energy demand for different locations such as Guayaquil and Atahualpa have been carried out in previous studies [15] [11]. The peak electrical load for a family composed of 5 members in Atahualpa parish is 0.97 kW. Based on the measurements, the higher period of energy demand occurs between 6 and 10 pm. Similar to the analysis in [12], it has been considered the electrical load for 12 homes, i.e., the maximum electrical load is established in 11.61 kW. In addition, for purposes of the simulations in HOMER, it has been considered a daily electric load variability of 2%.

2.3. Solar and wind energy potential assessment

Atahualpa RES potential has been evaluated from in-situ meteorological data collected during one-year period by the weather station. After processing this information and contrasting it with the satellite synthesized data by the NASA, confirms that Atahualpa has no considerable high wind speeds, but a good solar radiation intensity. The measured values of solar radiation range between 3.99 and 5.85 kWh/m^2 giving an annual average of 5.05 kWh/m^2/day. On the other hand, levels of wind speed ranged from 2.6 m/s to 3.27 m/s. The average annual wind speed is 2.84 m/s, more detailed information can be reviewed in [12].

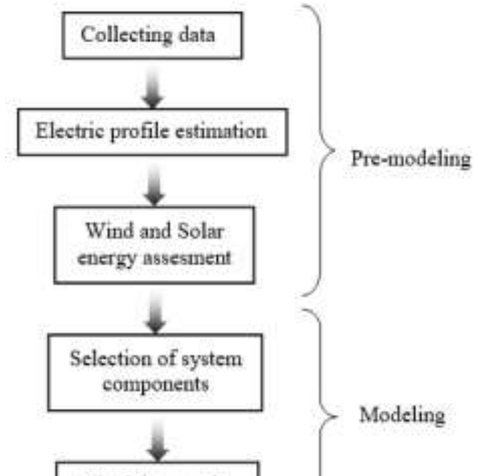

Fig. 1. Flow chart showing the steps executed in the present study [12].

2.4. Modeling and sensitivity variables

The implementation of a complete off-grid rural electrification system is not suggested if a feasibility analysis of the energy system is not carried out. Additionally, before the implementation and start up, several variables such as material cost, operating cost, benefits, etc. must be considered. In order to analyze such feasibility, system scale modeling appears a powerful tool to design and validate the possibility of building the off-grid system.

HOMER simulates and optimizes energy systems connected and disconnected to the grid. For this purpose, it performs three main processes: simulation, optimization and sensitivity analysis.

During the simulation process, the software considers the system components selected by the designer, electric load to be served, energy resource location and input parameters as shown in Table 1. Thus, it becomes possible to determine the energy balance of the HES for a year and generates possible system configurations that can meet the electric load demand. Moreover, HOMER optimizes the performance of each configuration during the simulation process, and displays an output-list based on the Total Net Present Cost (TNPC). The optimal configuration is the one with the lowest TNPC. The list of generated configurations can change in the optimization process based on sensitivity analysis of the variables which are entered by the designer. Finally, a new list of configurations based on sensitivity variables is re-generated. For this study, the following sensitivity variables are considered:

- Multiplier cost of the Photovoltaic-Array (PV-A): For each kW of PV-A, multiplicative factors of 0.6, 0.7, 0.8, 0.9 and 1 have been considered. It can be possible due to the downward trend in prices of PV-A or state incentives, e.g., 20% discount, HOMER simulates Capital Cost multiplier of 0.8 and then analyze the technical and financial viability of HES generating a new TNPC.

- Diesel Fuel Prices: two prices of diesel fuel used in electric generator are considered. The one subsidized by the Ecuadorian state for electrical purposes, $ 0.24/L [16], and the average world price, $ 0.83/L [17].

- Wind Scaled Average: in Atahualpa parish have been recorded wind speeds ranging between 2.27 and 4.67 m/s. For the sensitivity analysis the following values of speed in m/s are considered: 2.27, 2.84 (annual average), 3.27 and 4.67

3. System Specification

Basically, the proposed HES consists of PV-A, wind turbines and electric generator. There are several studies in other locations worldwide [18-25], in which the use of the electric generator is justified: i) as backup electricity during peak hours; ii) periods with few levels of solar radiation and wind speeds; and iii) to reduce the cost of electricity (COE) of the HES.

Nevertheless, in the mentioned studies, there is a fossil dependence which produces environmental impacts due to the emissions of greenhouse gases (GHG). Although from the chemical stoichiometry point of view, there is low impact on emissions when an electric generator uses diesel as fuel and not gasoline [26].

Figure 2 shows the design of HES simulates in Homer. It can be notice that wind turbines and PV-A generate electricity in Direct Current (DC), and the battery bank is loaded and unloaded in DC. The electric generator produces electricity in Alternating Current (AC), whereas that the converter transforms electric power from DC to AC in a process called inversion and serves the electric load demand in AC.

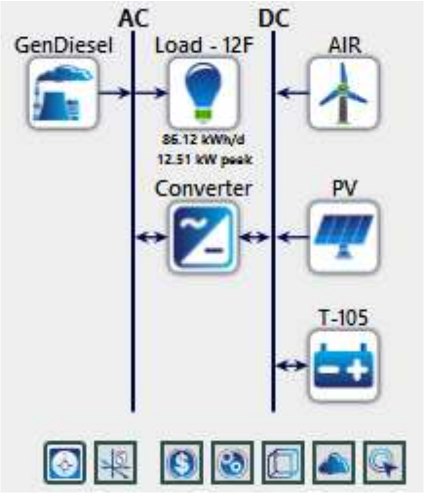

Fig. 2. Schematic of the HES design using HOMER.

Table 1. Summary of software inputs

Item	Size	Capital ($)	Replacement cost ($)	O&M ($/year)	Sizes (kW) considered	Quantities considered	Life time
PV Array	1	3000	2500	10	1-15		25 years
DC wind turbine	0.55	1200	1100	20		1-10	15 years
AC Generator (Perkins)	10	15231.42	2500/kW	0.3/h			15000 h
Battery (Trojan T-105)	230 Ah	150	130	10		170-230	845 kWh
Converter	1	300	250	10	8-16		15 years

Table 2. Optimized System – 36 % renewable resource utilization

System architecture		Annual electric energy production (kWh/year)			Annual electric energy consumption (kWh/year)			Emissions (kg/year)	
PV Array	5.33 kW	PV array	8734	24.58%	AC primary load	31423	100%	CO_2	17757
Wind turbines	7	Wind turbine	6798	19.13%	DC primary load	0	0	CO	43.83
AC Generator	10 kW	AC Generator	20001	56.29%	Total Cost summary	31423	100%	Unburned HC	4.86
Batteries	48	Excess	1163.8	3.3%	TNPC	$115766		Particulate matter	3.30
Converter	5.33 kW	Unmet load	11.1	0	Cost of energy	0.2813 $/kWh		SO_2	35.66
		Capacity shortage	13.1	0				NO_x	391.10

For financial analysis of the HES, nominal interest rates and the current annual inflation rate of 2015 according to the Central Bank of Ecuador [27] are considered, and the lifetime of the project is 25 years.

In addition, for each component of the system the investment costs, replacement costs and operation and maintenance (O & M) costs have been considered.

The system control in HOMER simulates dispatch strategies, the Cycle charging (CC) is considered, i.e., the batteries coupled to the HES are charged with the excess electricity when PV-A and wind generator are operating at maximum rated capacity. The values of parameters used for the simulation and optimization of the HES are shown in Table 1.

4. Results and Discussion

4.1. Optimization of hybrid renewable energy system

Results of simulation and optimization processes performed in HOMER are shown in Table 2. For these processes, the annual average wind speed of Atahualpa, i.e., 2.84 m/s at a height of 4 m, has been considered. In addition, the price of the diesel for the electric generator used in these simulations is $0.24/L, according to the official price list of Ecuador [16].

The most economical system cost, i.e., with the lowest TNPC, capital cost and COE for this HES are $ 115766, $ 48411 and $0.281/kWh, respectively.

Moreover, Figure 3 depicts the monthly distribution of the electricity produced in kW. We noted that the electric generator is the component that most contributes to the electricity production. This confirms the results of the simulation in which the renewable fraction of the energy delivered to the electrical load is only 36% in the optimal configuration of the HES, and an emission of more than 18 tons of GHG.

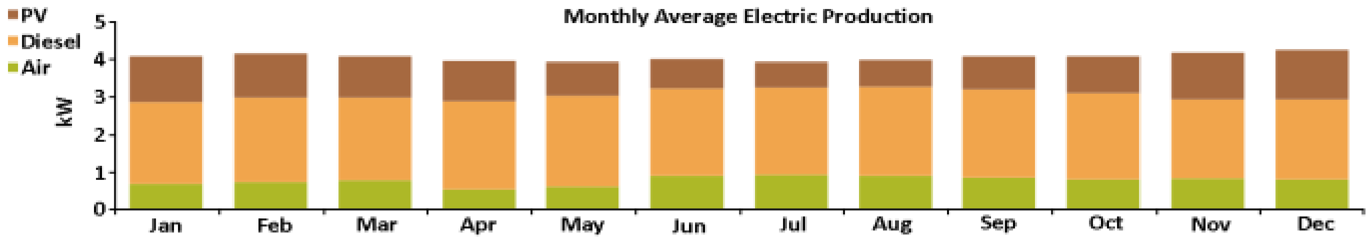

Fig. 3. Monthly average electricity production from HES optimized.

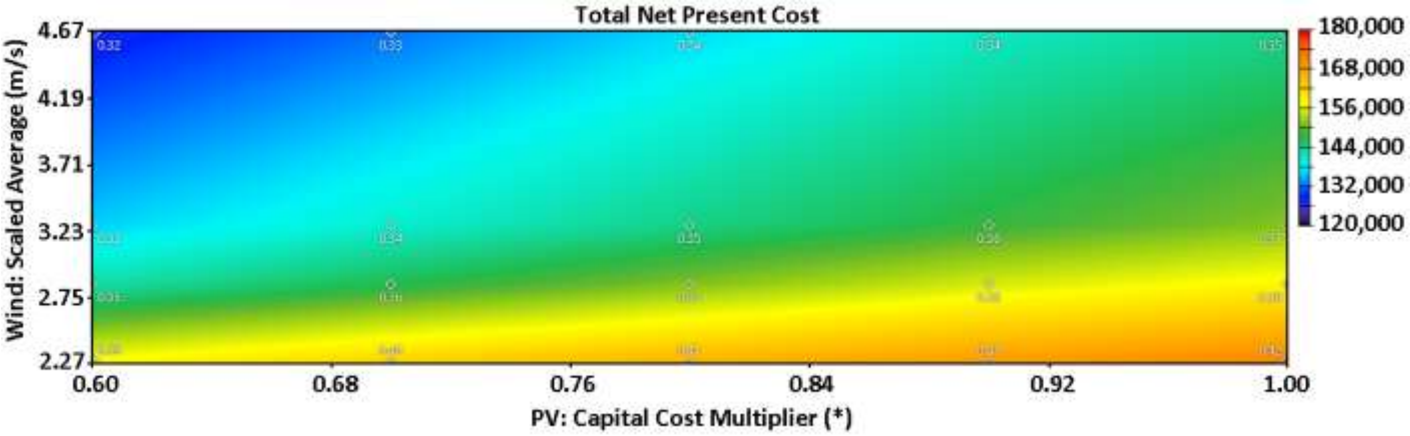

Fig. 4. Surface plot of TNPC, price of diesel at $ 0.83/L

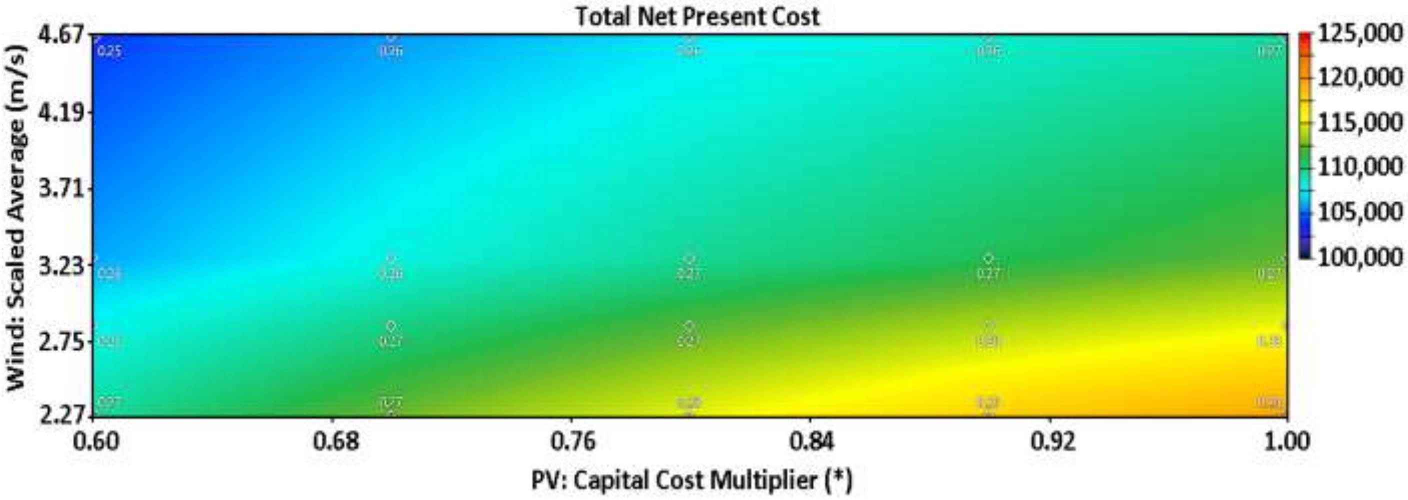

Fig. 5. Surface plot of TNPC, price of diesel at $ 0.24/L

The PV-Array produces 8733.8 kWh/year and operates 4349 h/year (capacity factor 18.72%). At this level of operation, the COE of PV System becomes just $0.146/kWh. On the other hand, wind generator produces 6798.1 kWh/year with a capacity factor of 20.16% (operating for 8077 h/year), and the COE of the wind generator is $0.15/kWh. Finally, the diesel generator produces 20,001 kWh year and operates 2131 hours/year with a capacity factor of 22.8% and COE of $0.068/kWh and fuel consumption of 6743 liters of diesel.

A total of 1163.8 kWh/year, i.e., 3.3% of the total electricity generated, goes unused due to low demand and is fed to dump loads. However, a related study [28] presents two possible benefits: HES could have the capability to serve a growing demand in the future; or it could also meet the demand of other nearby homes. Therefore, with increasing demand, the load factor is increased and the COE will decrease.

4.2. Consideration of sensitivity variables

As described in Section 2, three sensitivity variables were considered. The new optimal configuration was obtained with the sensitivity variables set with a PV multiplier factor of 0.6, price of diesel at $ 0.24/L and wind speed 4.67 m/s. The total system cost, capital cost and COE for this HES are $ 104213, $ 41160, $0.25/kWh, respectively. In addition, there is a slight contribution of FERs (40%) and a reduction of GHG (about 17 tons).

This HES is composed by 6.26 kW PV-Array, 6 SW-Air X turbines, 39 T-105 batteries, 5.38 kW Inverter and 10 kW Diesel Generator. This system produces 36681 kWh/year.

Figures 4 and 5 show the variation of the values of TNPC with price of diesel unsubsidized and subsidized by Ecuadorian state. Superimposed values refer to COE of the HES.

In these surface plots we can note the impact of the price of diesel in the values of TNPC and COE. The simulation results show that, if the price of diesel for electrical purposes is not subsidized, the electrical systems could be 100% FER, i.e., the diesel generator would be not necessary and the COE values could be \$ 0.316/kWh, \$ 0.327 kWh and \$ 0.339/kWh depending on system designed.

From Figure 5 it can be noted that the cost of 1 kWh (superimposed: \$0.25/kWh) is favored as PV price decreases and wind speed increases, i.e., the TNPC of the system will fall (near \$100000). However, the TNPC and COE will be more expensive (near \$180000 and \$0.42/kWh) when the above variations are not carried out and the price of diesel is not subsidized as depicted in Figure 4.

Conclusion

This work proposes an optimum design and economic evaluation of a HES composed by diesel electric generator. Compared to the study developed in [12] in which the TNPC is \$ 179928 and COE of \$ 0.44 /kWh, it is noted that with this new proposal (TNPC of \$ 115766 and COE of \$ 0.281 /kWh) the economical costs are lower. However, this HES emits more than 18 tons of GHG.

Moreover, considering sensitivity variables in this HES analysed, the TNPC and COE values could be about \$100000 and \$0.25/kWh, respectively.

Nevertheless, in both cases above mentioned the FERs contribution in the HES does not exceed 40%.

In addition, it can be noticed that in Ecuador, one residential user of an electric distribution company with consumption between 2501 and 3500 kWh/month must pay \$0.4260/kWh excluding other taxes [29]. In this HES proposed, the monthly electricity consumption of 12 families is about 3000 kwh.

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