Study of a Hybrid Wind-Photovoltaic System for Energy Supply to the Pucará Canton in Ecuador

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Abstract:
This article presents the analysis, modeling and simulation that describes the behavior of a hybrid photovoltaic and wind turbine system, taking advantage of the potential of the Pucará Canton in Ecuador. The numerical model based on the main equations was developed and the usable electrical power is highlighted.

This analysis has been carried out with the purpose that in the future these energy generation systems can be exploited for the benefit of the Pucará Canton according to the development plans foreseen by the Municipal GAD and the budget availability, in reality it is expected that this type of projects are pioneers in certain sectors.

Keywords: Modeling, Hybrid System, Renewable Energy, Energy and Management, Pucará, Ecuador

I. INTRODUCTION

The systematic use of traditional or non-renewable energy from the use of fossil sources is currently revealed as one of the main sources of environmental pollution, in addition to involving high costs for installation, maintenance and systematic purchase of fuels [1].

Several countries have focused on domestic production in the exploitation of non-renewable natural resources such as oil and natural gas, showing in recent decades the need to diversify the economy and make optimal use of renewable natural resources [2]–[5]. On the other hand, it is necessary to reduce the levels of pollution that currently affect the natural environment.

Centuries of exploitation and destruction of renewable and non-renewable natural resources in Ecuador have caused the stagnation of national economic development [6]. The increase in pollution levels and the dependence on the import of goods and services from abroad continue until now, in reality, technological development still needs to take off [7].

Historically, Ecuador's energy needs, despite having a wide range of energy resources, are supplied by 89% from the use of oil as a non-renewable natural resource for the production of electricity [8].

Similarly, A. AlKassem et al. [9] highlights that in recent decades there has been a sustained growth in energy demand, verifying that it is 1.9 times higher than the average GDP growth. This situation is due to the non-existence of an energy planning policy that guarantees an effective use of the country's economic resources [10], [11].

With the aim of developing the national industry, as well as making optimal use of renewable resources, various hydroelectric projects have been developed [12], such as Mazar, Sopladora, Ocaña, Coca Codo Sinclair, Toachi Pilatón, Delsintanisagua, Minas San Francisco, Manduriacu, and the Villonaco wind farm [13]; in order to increase the country's energy production and reduce dependence on non-renewable resources such as oil and natural gas [14].

As a consequence of the overexploitation of non-renewable energy resources, pollution rates have increased significantly in the last three decades in such a way that endemic natural species of the country have been lost or their populations have been alarmingly reduced [15]. On the other hand, in certain regions of the country, the effect of the acidity of the land can be felt, which has lost its fertility, transforming into desert areas [16].

Particularly in relation to the present study, the continuous growth of the population has led to a progressive concentration in large urban centers such as Pucará and the highly visible industrial development causes day by day more problems to the environment known as the effect [17]. At present, the development of wind-photovoltaic hybrid systems at the national level is limited, largely due to the high initial cost of this type of structure [18]. On the other hand, Ecuador, being a country that produces natural gas and oil, has extremely low prices compared to the international market for these fuels [19].

AJ Njoh et al. [20] highlighted the opportunities and challenges for rural renewable energy projects in Africa. He mentioned the case of the Esaghem Village solar electrification project, Cameroon.

Furthermore, reference [21] and [22] presented and analyzed the techno-economic feasibility of using wind and solar energy in renewable energy applications to form hybrid systems. Another study was carried out by reference [23] for the implementation of hybrid systems in rural and marginal urban areas disconnected from the public power grid. In this study, its energy potential will be analyzed so that it can be implemented in the future [24].

Another study was proposed by M Sarr et al. [25] for Senegal and made available to the SENELEC company in which the maximum rate of penetration in photovoltaic energy is determined. P Carroll et al. [26] developed the grid codes to facilitate the energy transition experienced by different countries that are seeking to move from fossil fuels to an energy system based on renewable energies. In this sense, L Steg et al. [27] invites us to understand the human dimensions of a sustainable energy transition in which it would be fulfilled in the long term. Another interesting study is presented by N Kittner et al. [28] in which I develop a methodology for the storage of clean energy in the energy transition process.

II. LOCATION OF RESEARCH

Pucará is located to the South West of the province of Azuay, it has a territorial extension of 749 km2, it comprises two parishes: the urban "Pucará" and the rural "San Rafael de Sharug" with a total of 64 communities.

It has three climatic zones from 200 meters above sea level to 4000 meters above sea level, making it a canton with prodigious diversity in flora and fauna; with a wide variety of gastronomy and landscapes. It limits to the North with the Camilo Ponce Enríquez canton, to the South and West with the Pasaje canton and to the East with the Santa Isabel Canton [29], see figure 1.

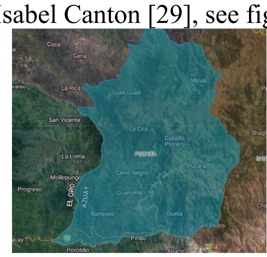


Fig 1.- Location of Pucará Canton in Ecuador.

Pucará, is a term of Quechua origin that means Fortress or elevated place of prayer; The cantonal center is located between two hills "Zhalo" and "Barishigua" which, according to our ancestors, were used by the Incas as a strategic place of defense or combat position for war.

Among the most notable tourist attractions are: Cerro Zhalo, Mirador de Patococha, Laguna de Ñarigüiña, Piedras Picotas, Cara del Inca, Baño del Inca, Piedra Ataúd; Ñugropamba Waterfall, La Resbaladera Waterfall, Cerro Negro Waterfall, La Chonta Waterfall, La Cascada, Río Vivar, among others.

Next, figure 2 presents a diagram of the hybrid system with wind and photovoltaic energy inputs. In our case study we consider it without connection to the public electricity network.

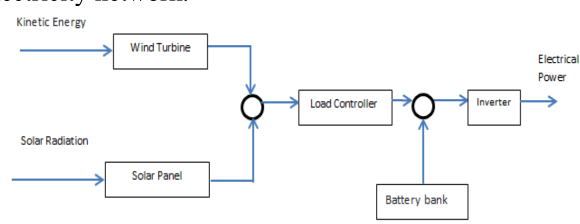


Fig 2.- Hybrid system with its main components

III. MATHEMATICAL MODELING.

Next, in the simplified mathematical model, the main equipment that will directly influence the final objective, which is the generation of energy by renewable sources, is presented. Subsequently, the simulations are carried out with the help of the energy conversion equations of each contribution, both wind and photovoltaic [30]–[32]. This process ultimately allows us to design the system based on the wind and solar potentials found on the site. This research will give rise to new analyzes in the Canton and lead to a greater discussion for the electrification processes as it has been carried out in other developed areas such as the one presented by JD. Jara et al [33].

A. Wind turbine Simulation:

The power of a particular wind turbine is given by;

$$P_{WT} = 0.5 * C_{p1} * \rho_{air} * A * v^3 * \eta_{aer} \qquad (1)$$

Where; P_{WT} = Wind power sweep produced by the blades per unit area. C_{p1}= Betz power coefficient. ρ_{air}=Air density, A is the Area swept by the blades of the wind turbine and v is the wind velocity [34].

B. Photovoltaic PV system:

The hourly output of the photovoltaic module is related to the intensity of the light that is received by the photovoltaic module. The ambient temperature and the characteristics of the photovoltaic module will also influence the conversion process to electrical energy.

Assuming that the maximum power point tracker (MPPT) is used and that the photovoltaic module is always operating at the maximum power point given the very good conditions of the Pucará Canton, the formulas to calculate the current and voltage are analyzed in the optimum point of operation and has the following forms [35]:

$$I_{PV} = I_{SC}\cdot \left\{1 - C_1\cdot \left[exp\left(\frac{V_{PV}-\Delta V}{C_2 \cdot V_{OC}}\right) - 1\right]\right\} + \Delta I \quad (2)$$

Where:

$$C_1 = \left(1 - I_{mp}/I_{SC}\right) \cdot exp[C_2 \cdot V_{OC}] \quad (3)$$

$$C_2 = \frac{\frac{V_{mp}}{V_{OC}}-1}{ln\left(1-I_{mp}/I_{SC}\right)} \quad (4)$$

$$V_{PV} = V_{mp} \cdot \left[1 + 0.0539 \cdot lg\left(\frac{E_{tt}}{E_{st}}\right)\right] + \beta_0 \cdot \Delta T \quad (5)$$

$$\Delta V = V_{PV} - v_{mp} \quad (6)$$

$$\Delta I = \alpha_0 \cdot \left(\frac{E_{tt}}{E_{st}}\right) \cdot \Delta T + \left(\frac{E_{tt}}{E_{st}} - 1\right) \cdot I_{SC} \quad (7)$$

$$\Delta T = T_{cell} - T_{st}, T_{cell} = T_A + 0.02 \cdot E_{tt} \quad (8)$$

Where:

β angle of inclination of the plane to the ground (deg)
T_A ambient temperature under arbitrary conditions (°C)
E_{st} standard light intensity (1000 W/m^2)
I_{SC} module short-circuit current (A)
E_{tt}, E_{th} total irradiance incident on tilted plane and horizontal surface (W/m^2)
V_{mp} module maximum power voltage (V)
V_{OC} module open circuit voltage (V)
α_0 module current temperature coefficient (A/°C)
T_{cell} Cell temperature
V_{mp} module maximum power voltage (V)
V_{PVA} PV generator output voltage (V)

C. Controller:

The controller power output is given by;

$$P_{Cont-dc} = V_{bat}(I_{wind} + I_{PV}) \quad (9)$$

Where; V_{bat} is multiplication of the nominal voltage DC for the currents of PV and wind.

D. Battery charging and discharging Model:

The battery stores excess power going through the load controller. The battery keeps voltage within the specified voltage and thus, protects over discharge rates, and prevent overload.
During the charging period, the voltage-current relationship can be described as follows;

$$V = V_r + \frac{I\left(\frac{0.189}{(1.142-soc)+R_i}\right)}{AH} + (soc - 0.9)\ln\left(300\frac{I}{AH} + 1.0\right) \quad (10)$$

And;

$$V_r(V) = 2.094[1.0 - 0.001(T - 25°C)] \quad (11)$$

However, during the discharging process and using equation (11), the current-voltage can be;

$$V = V_r + \frac{I}{AH}\left(\frac{0.189}{soc} + R_i\right) \quad (12)$$

And R_i is given by;

$$R_i(\Omega) = 0.15[1.0 - 0.02(T - 25°C)] \quad (13)$$

Where,
$V_r(V)$, I: the terminal voltage and current respectively
$R_i(\Omega)$: Internal resistance of the cell and T is the ambient temperature.
AH: Ampere-hour rating of the battery during discharging process
The power produced by the PV array can be calculated by the following equation,

$$P = V\ I_{OUT\ rect} \quad (14)$$

Where $I_{OUTrect}$ represent the total output current of the rectifier in DC (10).

E. Inverter:

The characteristics of the inverter are given by the ratio of the input power to the inverter P_{inv-ip} and inverter output powerP_{inv-op}. The inverter will incur conversion losses and to account for the inverter efficiency losses, η_{inv} is used;

$$P_{inv-ip}.\eta_{inv} = P_{inv-op} \quad (15)$$

Next, in Fig 3, the meteorological data in the Pucará Canton referring to the 12 months of the year extracted and ordered from historical data from NASA. Fig 4 shows the energy conversion flowchart.

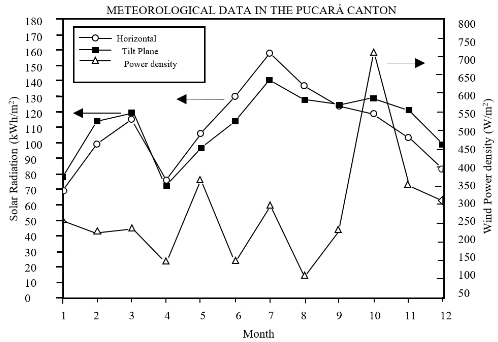


Fig 3.- Meteorological data in the Pucará Canton

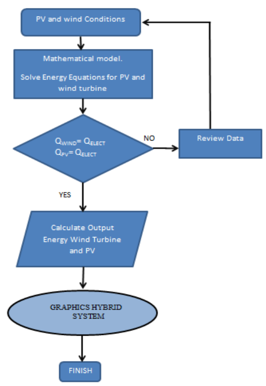


Fig 4.- Flow chart of the wind-photovoltaic energy conversion system

IV. RESULTS AND DISCUSSION

After having defined the main equations that intercede in the hybrid wind-photovoltaic system for the use of energy in the Pucará Canton, taking into account that the total power may not be simultaneous or constant, which is the reason for a hybrid system to maintain active to the generation system with a battery backup for the hours of lack of energy power. For validation purposes, the simulation model used and the mathematical relationships described above were coded to define their possible results of the formation of the hybrid system. To achieve the simulated results and obtain the output power of a system, the simulation tool such as matlab was used for simulation under various conditions.

Next, in Fig 5 and Fig 6, the profile of solar radiation and wind speed in the Pucará Canton is presented in the period of one year.

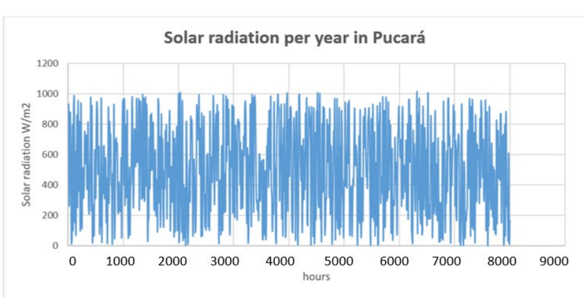


Fig 5. Solar radiation per year in Pucará-Ecuador

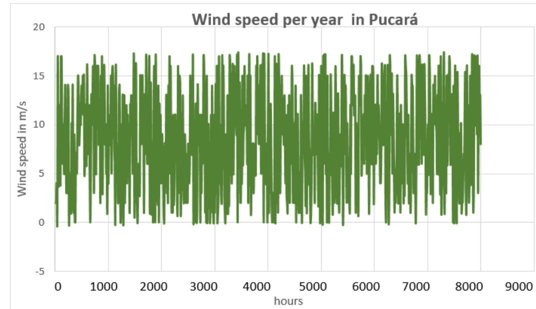


Fig 6.- Wind speed per year in Pucará-Ecuador

Approximate load data are considered based on the population of the place, surely it will be helpful in the real feasibility study for the implementation of the hybrid renewable energy system for the Pucará Canton. The load profile is presented in Fig 7.

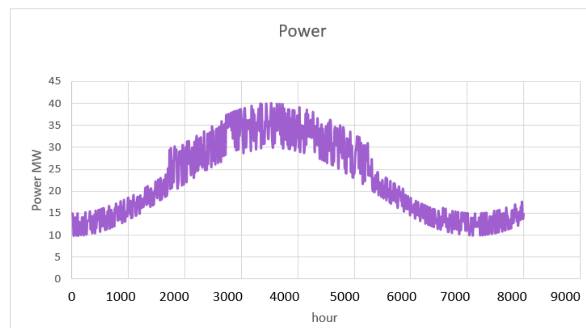
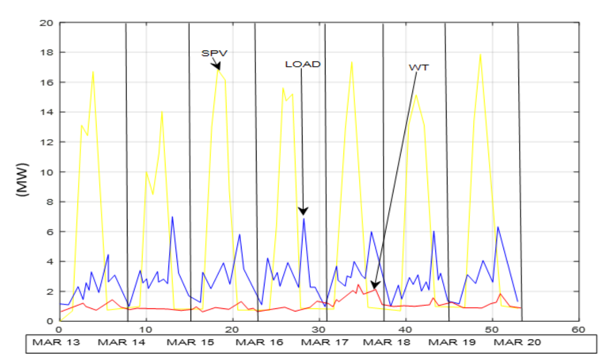
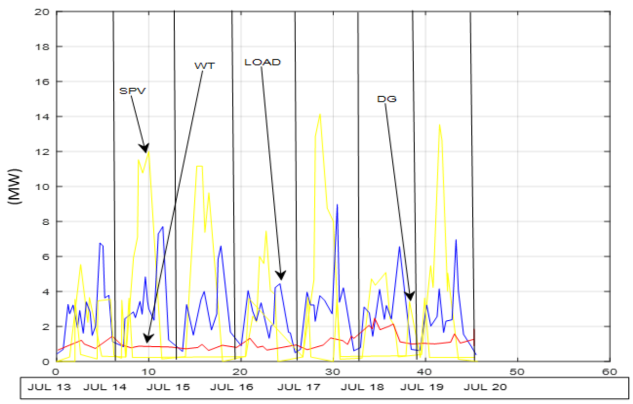


Fig 7. Load profile considered.

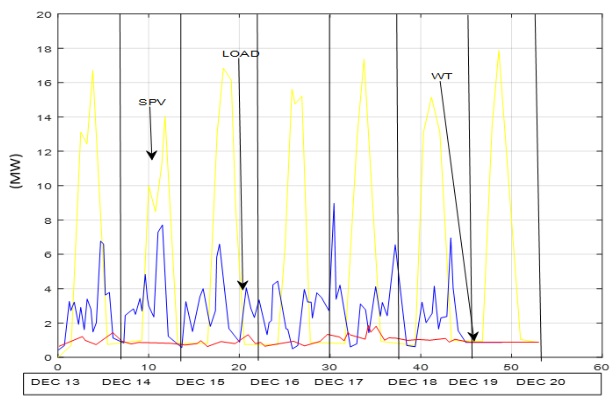
Fig 8 shows that the accumulated electrical power generation is always greater than the load demand in all three cases analyzed, both in January, July and December. In the summer season (Fig 8a, March), the renewable energy is sufficient for the load demand and no backup is needed, in this case the PV system generates the maximum power and WT supports the PV as shown in fig 8 (a). The PV and WT system reduces generation in the winter season (Fig 8b, July). In winter season, renewable resources are enough to meet load demand.



(a) Electric power generation in summer (example, March)



(b) Electric power generation (example, july)



(c) Electric power generation (example, December)

Fig 8. Electricity generation pattern

V. CONCLUSIONS

The mathematical relations of energy conversion that describe the hybrid system of wind turbine and photovoltaic.

Although the production of electrical energy due to the wind source is not preponderant with respect to solar photovoltaic, it is a support to maintain continuity in the production of energy and avoiding, as much as possible, that the storage system is discharged in high percentages.

In Figure 8 it can be clearly identified that throughout the year it is possible to maintain high levels of energy production despite the existence of variations in the referential seasons of the year.

According to the results of the photovoltaic study, they showed that the greater the solar radiation in the Pucará Canton, the greater production can be achieved, even if the photovoltaic solar panels are of very good efficiency, it is possible to have greater electrical power. Consequently, the higher the solar radiation, the higher the PV power and PV current.

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