VIABILITY STUDY OF A HYBRID PHOTOVOLTAIC, WIND AND BATTERY SYSTEM FOR DIFFERENT REGIONS OF BRAZIL

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Abstract. *With many renewable energy sources available, the combination of them becomes an interesting investigation. The hybrid photovoltaic, wind, battery system is a combination of solar and wind energy with a battery bank for energy storage, and it has been widely studied in the last years. Such a hybrid system has been shown as a solution for many energy problems around the world, and then it must be analyzed to applications in Brazil intending to investigate in which regions it could be applied with the purpose of making the most efficient and cheap energy generation. In this paper is described a study about the viability of this hybrid system for some regions of the country. Each subsystem is sized based on global irradiance, wind speed data and load demand. The percentage of the generation subsystems required to supply the load demand is calculated, and then the most efficient combination is selected. Each region has its own climatic characteristics, which implies that the most efficient system is composed of a different combination of the subsystems. Most of Brazilian territory has high availability of solar energy; on the other hand, wind power is more restricted on some areas, hence the proposed hybrid system is restricted to where there is availability of both sources, which represents many inland and coastal regions of Brazil. The technological development of these subsystems and its observed potential for many regions shows that the analyzed hybrid system is a good alternative for energy solutions in many locations of the country.*

Keywords: *Solar energy, Wind energy, Hybrid system*

1. INTRODUCTION

In developing countries, like Brazil, the energy demands have been grow in the last years, which implies in a more rigorous planning about the use of the energy resources. With many renewable energy resources available, one of the most important issue is to balance which are better to implement. Since the country has the availability of different energy sources, combining these in a hybrid system will vary from place to place. Nowadays, an important hybrid system that have been used and studied is the integration of photovoltaic and wind energy sources with a battery array for storage. These different resources have an unpredictable behavior and depends on weather conditions, which leads to the idea of an integration of them in a way that one can overcome the absence of the other, i.e. when one source is scarce, the other will supply the remaining demand and vice versa.

Many researches study an optimal hybrid PV-wind-battery system for different regions of the globe (Bahta, 2013) (Shiroudi *et al*, 2012). The interest about this combination is explained due two main reasons: 1) the three items that composes the system are in a growth technological development, which makes it more efficient, reliable and with a better cost-benefit during the years. Furthermore, the industry believe that the photovoltaic and wind energy resources and the battery storage system will develop an important role in the solution of the world's energy problems (Divya and Østergaard, 2009) (Ferreira, 2008) (Razykov *et al*, 2011); 2) both solar and wind are sources available for a large percentage of the world's territories, making their use attractive in such places.

Wind and Photovoltaic energy have a good potential in a large portion of the Brazilian territory (Ferreira, 2008) (Martins *et al*, 2008), which makes this hybrid system an important candidate to be investigated and analyzed. This system could be an alternative to reduce the dependence of the hydropower, which depends on the seasonal rains; or even to bring electricity to the innermost regions without the need to build electric grid lines, reducing the plant installation and maintenance costs. In this way, this paper presents a study about the viability of the use of a battery storage hybrid standalone (off-grid) photovoltaic-wind energy supply system for some Brazilian regions.

2. HYBRID PHOTOVOLTAIC, WIND, BATTERY SYSTEM SIZING

Hybrid Power System is a combination of different energy resources, which can be renewable or not renewable. In the case of renewable ones, due to the unpredictable behavior and dependency on weather conditions of the resources, it is expected that when one of these sources is scarce the other will supply the energy demanded, however, on the absence of generation, a storage subsystem can be implemented to supply the load. An important hybrid system that have been studied in these last years is the combination of solar and wind energy, which can be explained due to the importance of these energy sources individually (Filgueiras *et al*, 2003) (Martins *et al*, 2008) (Patel *et al*, 2005) (Razykov *et al*, 2011).

Photovoltaic panels are devices used to convert solar irradiation into electrical energy. In the same way, the wind turbines extract the energy in the wind to produce electrical energy using a generator. Both these sources play the role of a generation subsystem for the proposed hybrid system (Fig. 1), where the produced electrical energy can be directly used to supply the load demand through an inverter, which converts DC current to AC current. To improve the system, a battery bank is integrated to it for storage purposes, therefore, the energy generated by the photovoltaic cells and wind turbine that is not demanded can be stored for future use.

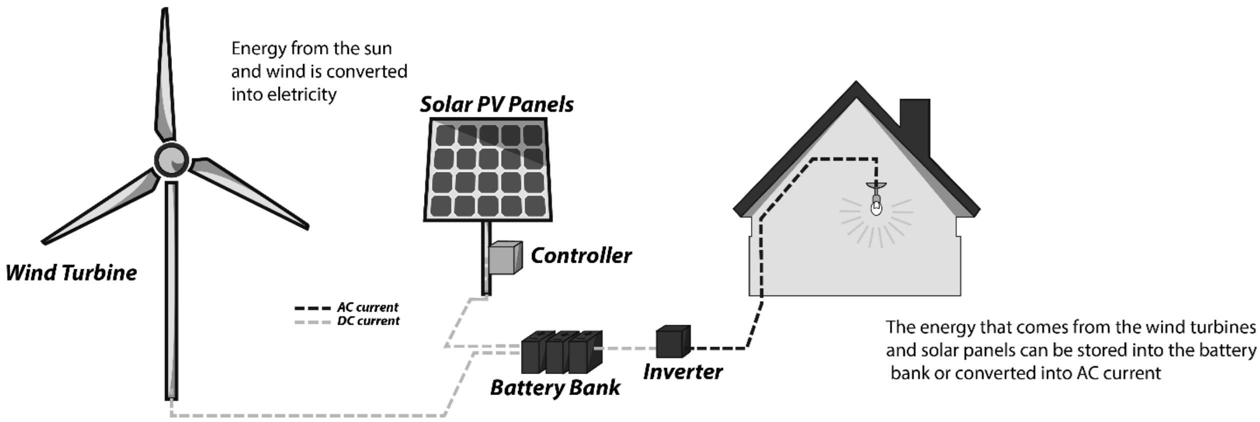

Figure 1- Hybrid photovoltaic, wind, battery system scheme.

In Brazil, there is a wide availability of such sources (Ferreira, 2008) (Martins *et al*, 2008), which creates the importance of observing if the combination of both is feasible. Here, a small off-grid hybrid photovoltaic-wind-battery system is analyzed for application in some regions of Brazil, intending to observe the viability of it for different regions of the country. This could be an option for the installation of grid lines in these areas, reducing costs of installation, maintenance, replacement and others. This analysis is only a first overview of such a system. Therefore, some details are neglected as the inverter efficiency, the energy losses in the lines, the dynamics of the system and others.

2.1 Photovoltaic solar panels and wind turbines sizing

Solar Photovoltaic is one of the subsystems for energy generation, which convert solar energy into direct current electricity using a solar cell and a controller. This electrical energy can supply the load demand or be stored in the battery bank. For the presented analysis, some important equipment characteristics are adopted: $A_{PV,u}$ (1.94 m²) is the area of each PV module unit, η_{PV} (12%) represent the PV conversion efficiency, $\eta_{PV,controller}$ (90%) represents the controller efficiency and $P_{PV,u}$ (276.2 W) is the rated power per unit.

Given the data of daily global solar radiation G_r on a horizontal surface, its integration obtains the daily available energy per unit area. Then, in the same way, monthly available solar energy per unit area (or specific solar energy available) E_{solar} can be calculated. Thus the specific energy generated by the photovoltaic subsystem for each month is

$$E_{PV,m} = E_{solar,m} \cdot \eta_{PV,controller} \cdot \eta_{PV} \tag{1}$$

Wind resource plays the role of a second subsystem for energy generation. For such purposes, a wind turbine can be used for wind energy extraction. Wind speed is responsible to rotate the turbine blades connected to a generator, which converts the rotational energy into direct current electricity. As in the PV subsystem, the converted current can either feed the lead demand or be stored in the battery bank. Some important equipment property are adopted as: $A_{WT,u}$ (1.08 m²) is the area of each wind turbine unit (rotor sweep area), C_p (0.35) represent the power coefficient, h (30 m) is the wind turbine hub height, η_g (90%) represent the generator efficiency and $P_{WT,u}$ (160 W) is the rated power per unit.

To estimate the available energy in the wind, data of speed frequency for each month is required to obtain the monthly mean wind speed.

$$\bar{V}_{wind,m} = \int_0^{\infty} V. f(V). dV \tag{2}$$

where $f(V)$ is the relative frequency of the wind speed V during the month. Then, the wind speed data for each month must be extrapolated to the hub height (Bahta, 2013). Therefore, the specific power available in the wind for each month is

$$P_{s,wind,m} = \frac{1}{2}. \rho. \bar{V}_{wind,m}{}^{3} \tag{3}$$

where ρ is the air density and $\bar{V}_{wind,m}$ is the monthly mean wind speed. This specific power is integrated along the month to calculate the specific energy in the wind $E_{s,wind,m}$. Then, the energy generated by the wind turbine per unit area is obtained, which represents the energy extracted by the rotor blades.

$$E_{WT,m} = E_{s,wind,m} \, . \, \eta_g \, . \, C_p \tag{4}$$

The power coefficient C_p is a function of the tip speed ratio (TSR) of the turbine and can be interpreted as the ratio between the extracted energy by the wind turbine and the total energy available in the wind. In this study, for simplification purposes, this coefficient will be assumed as constant.

Energy generation in the proposed hybrid system, as observed, is dived in two parts. In order to represent the contribution parcel of each subsystem, the coefficient f_{PV} represent the photovoltaic generation fraction. Therefore, if $f_{PV} = 1$, it correspond to a hybrid system where all the energy generation is based on photovoltaic subsystem. Thus, the monthly balance of energy generated by each subsystem can be related to the monthly energy demand M_D. Electrical load demand is assumed constant in the presented analysis and must be wholly supplied by the photovoltaic-wind-battery system, since it is an off-grid installation. The mean daily load demand is adopted as 10 kWh, which is the average consumption of the Brazilian population, and the monthly load demand depends on the number of its days.

$$\begin{gathered} A_{PV} \, . \, E_{PV} = f_{PV} \, . \, M_D \\ A_{WT} \, . \, E_{WT} = (1 - f_{PV}) \, . \, M_D \end{gathered} \tag{5}$$

To size the photovoltaic and the wind turbine subsystems, the generation and demand are analyzed monthly. The generation subsystems areas (A_{PV} and A_{WT}) and required installed power P_{PV} and P_{WT}) are observed for different values of f_{PV} in each month by

$$A_{PV} = \frac{f_{PV} \, . \, M_D}{E_{PV}} \qquad\qquad A_{WT} = \frac{(1 - f_{PV}) \, . \, M_D}{E_{WT}} \tag{6}$$

$$P_{PV,req} = \frac{A_{PV} . E_{PV}}{24 \, . \, n} \qquad\qquad P_{WT,req} = \frac{A_{WT} . E_{WT}}{24 \, . \, n} \tag{7}$$

where n is the number of days of each month. Knowing these values of required installation area and the area of each unit of the generation subsystems, it is possible to determine the number of photovoltaic panels N_{PV} and of wind turbines N_{WT}, which must be rounded up for a real representation. The number of photovoltaic panels and wind turbines is multiplied by the rated power of each component to obtain the total installed power, for each case.

$$P_{inst} = P_{PV,u} . N_{PV} + P_{WT,u} . N_{WT} \tag{8}$$

To select the best combination a three-step process is proposed. Firstly, all generation systems designed varying f_{PV} in each month are observed for the available energy in the other months. Thus, if it can provide energy during all the year (assuming that the monthly demand is the maximum load of the year, i.e., 310 kWh), the system is selected for further analysis. Secondly, it is analyzed if the selected systems has a total installed power higher than the required. And finally, each selected system has its efficiency evaluated as:

$$\eta_{sys} = \frac{P_{d,req}}{P_{inst}} \tag{9}$$

where $P_{d,req}$ is the power required by the load demand, assuming it constant. It is expected that the selected system will be the one that was designed for the month where the available energy by the resources is the lowest one. The achieved system represent the photovoltaic and wind turbine power combination required to cover the monthly average load, thus, their values must correspond to an oversized system since this analysis does not take into account the daily variations in demand and energy availability or even the presence of a storage system. Therefore, the presented study is just a first sight of such a hybrid system.

2.2 Battery bank sizing

Due to the stochastic nature of the photovoltaic and wind turbine energy production, the proposed hybrid system will require a storage subsystem. It will be responsible to guarantee energy supply in a day where demand exceeds generation, and also it must deal with the system energy fluctuations. During periods of relative high bright sun and wind speed (high level of power generation), if all this energy is not immediately required to supply the load on demand, the excess of power can be stored for future necessity. Since the daily demand is assumed as constant, the battery sizing will be performed in a simplified manner. Assuming that the storage subsystem can supply energy for the load demand during

N_{days} without the need to be loaded during this time and that the discharge efficiency is 100%, the number of batteries N_{bat} is given by

$$N_{bat} = \frac{N_{days} \,.\, D_d \,.\, 1000}{V_b \,.\, S_b \,.\, DOD_{max} \,.\, \eta_{bat}} \tag{10}$$

where D_d is the load daily demand, V_b (12 V) is the battery bank voltage, S_b (220 Ah) is the battery capacity, DOD_{max} (80%) is the maximum depth of discharge and η_{bat} (85%) is the battery efficiency during charge. The number of batteries must be rounded up. Once the demand is constant, the design of the battery bank is independent of the generation system. Therefore, as for the generation subsystem, these numbers are just a first and simplified view of such a hybrid system.

2.3 Cost analysis

After the subsystem selection of more efficient generation and storage system analysis, the hybrid system cost is evaluated for an economical observation. Since it is a general analysis, only the capital cost is considered, and are not taken into account other important costs such as maintenance, replacement, installation, etc. Then, it is assumed that the system has a service life of 20 years, and that its value will be paid during this period over an annual percentage rate of 14%. Tab. 1 shows the initial cost assumed for each equipment.

Table 1 – Subsystems assumed initial cost.

C_{PV}	C_{WT}	C_{bat}
R$ 1,400.00 per unit	R$ 5,499.00 per unit	R$ 1,720.00 per unit

2.4 Database

In order to obtain most accurate results, it is important the usage of a reliable database, because any variations that do not correspond to reality can result in a hybrid system that does not match to the desired one. Thus, the quality of data (solar radiation, wind speed) becomes critical to the presented analysis.

Two databases are used in this paper. The first, and most important, is the result of project SONDA (National Organization System of Environmental Data applied to the energy sector), which was developed by the Weather Forecasting and Climate Studies Center (CPTEC / INPE). Its main objective is the implementation of a framework of environmental data collection required for observation and planning use of wind and solar energy in Brazil. The second database is a result of Solar and Wind Energy Resource Assessment (SWERA), project that was developed in order to improve availability and accessibility of information relating to wind and solar sources in the world. Within the developers of this project is the CPTEC / INPE. The data on solar radiation and wind speed are publicly available on their respective websites (INPE, 2015) (NREL, 2015).

The data used are for the year of 2014. In addition, about 1% of the data provided by the databases are regarded as lost, thus, a linear interpolation and extrapolation have been implemented in order to facilitate the studies.

3. RESULTS AND DISCUSSION

The analysis was performed for three different cities. Two of them are São Martinho da Serra and Florianópolis. The choice of them is due the availability of a reliable database of solar irradiance and wind speed. A third hypothetical city was simulated to observe effects that do not occur in previous cities. This allows a better understand the advantages of the hybrid system under study.

São Martinho da Serra is located in the interior of Rio Grande do Sul, latitude 29°26'34"S and longitude 53°49'23"W, at an altitude of 489 m. This city has a reasonable level of sunlight, and, although there are oscillations between summer and winter, the solar specific energy is almost constant throughout the year, showing that probably the use of solar systems is advantageous. On the other hand, the monthly average wind speed is relatively low (around 2.24 m/s at 10 m), decreasing the likelihood of using a wind power system. Given the efficiency of the considered generation subsystems, it is possible to estimate the amount of useful energy throughout the year for each of them, as shown in Fig. 2.

The amount of useful energy from the photovoltaic system is larger than the wind turbine system. Thus, it is expected that the hybrid system have a higher percentage of solar system installed than wind systems. Most selected systems (that are able to provide power throughout the year) are those for the months in which there is less available energy from the sources, i.e., March and May. Among all them, the most efficient is chosen and integrated with a battery bank, which can supply the load demand for 3 days. Its characteristics are shown in Tab. 2 and its behavior along the year in Fig. 3.

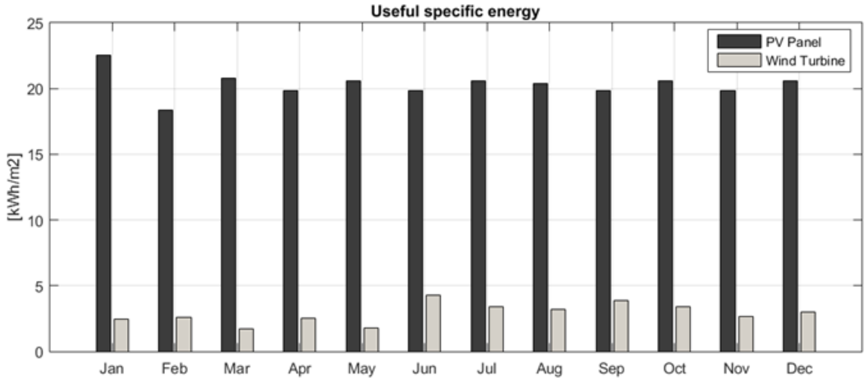

Figure 2- Useful energy per square meter in São Martinho da Serra.

Table 2 – Selected hybrid system for São Martinho da Serra.

Most efficient system for São Martinho da Serra						
η_{sys}	f_{PV}	$P_{inst,PV}$	$P_{inst,WT}$	N_{PV}	N_{WT}	N_{bat}
11.42%	0.9	2209.6 W	1440.0 W	8	9	17

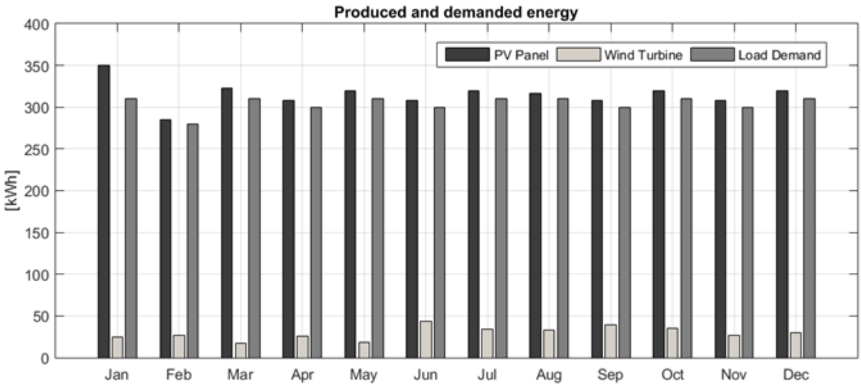

Figure 3- Performance of the most efficient system for São Martinho da Serra.

Similarly, an analysis is performed to another city in southern Brazil: Florianópolis, the state capital of Santa Catarina, located in the country's coast. Its location is given by latitude 27°36'6.1"S and longitude 48°31'4.2"W at an altitude of 31 m. In the same way, this city has a reasonable level of solar incidence, almost constant throughout the year and a relatively low average wind speed along the year (around 2.27 m/s at 10 m).

The proportion of solar energy compared to wind energy is high. Therefore, we expect a system with high percentage of installed photovoltaic as well as in São Martinho da Serra. The selected system (most efficient) was integrated with a battery bank, which can supply the load demand for 3 days and its characteristics are shown in Tab. 3 and Fig. 4 represents its performance along the year.

Table 3 – Selected hybrid system for Florianópolis.

Most efficient system for Florianópolis						
η_{sys}	f_{PV}	$P_{inst,PV}$	$P_{inst,WT}$	N_{PV}	N_{WT}	N_{bat}
16.76%	1.0	2485.8 W	0 W	9	0	17

It can be seen that the most efficient system is purely photovoltaic and, as daily demand does not change, the battery bank size stays constant. Thus, it is observed that in case of this city, the use of a hybrid system (photovoltaic/wind/battery) is unnecessary. That is, because the constancy of solar radiation throughout the year, a purely photovoltaic system becomes more feasible.

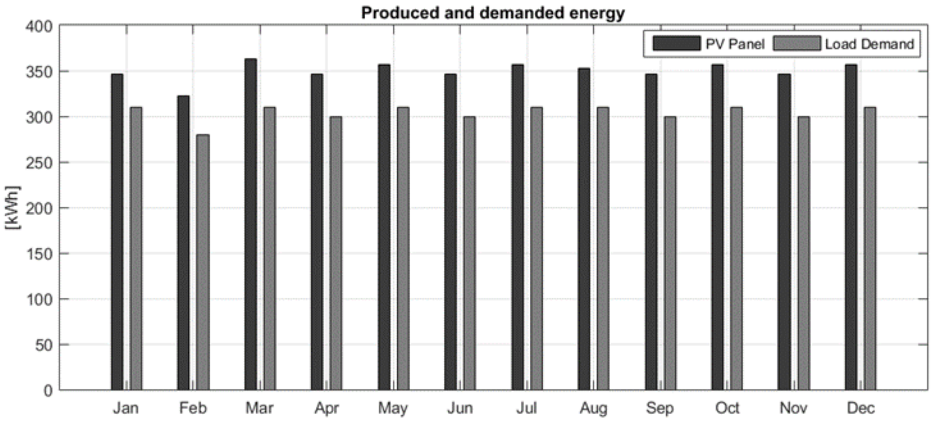

Figure 4- Performance of the most efficient system for Florianópolis.

A hypothetical third city is analyzed to simulate a region where the solar incidence is stable during the year and the annual mean wind speed is higher (5.52 m/s at 10 m), which represents some regions of Brazil. It is assumed that solar irradiation is the same as São Martinho da Serra. Fig. 5 shows the wind speed to the three analyzed cities.

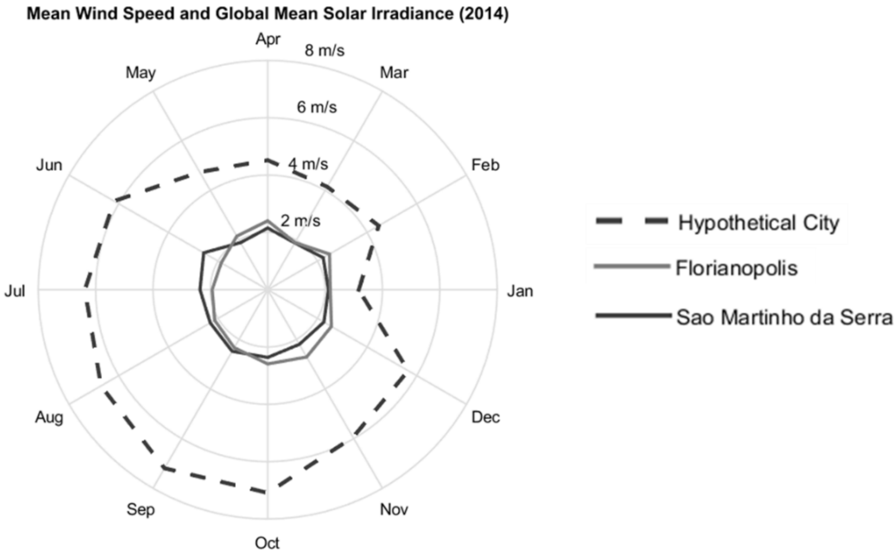

Figure 5- Mean Wind Speed for different cities.

It can be seen that the wind speed, and consequently, the wind turbine useful energy, is greater between July and December, where there is more power available from the wind than the solar radiation. However in the other months, although there is a stable solar energy, the wind energy is lower, which makes these months more critical. This third scenario is analyzed and the most efficient system is selected, which, as the other, is connected to a battery bank capable to supply the load demand for 3 days. Tab. 4 and Fig. 6 shows the performance of this selected system along the year.

Table 4 – Selected hybrid system for the hypothetical city.

Most efficient system for hypothetical city						
η_{sys}	f_{PV}	$P_{inst,PV}$	$P_{inst,WT}$	N_{PV}	N_{WT}	N_{bat}
17.26%	0.8	1933.4 W	640 W	7	3	17

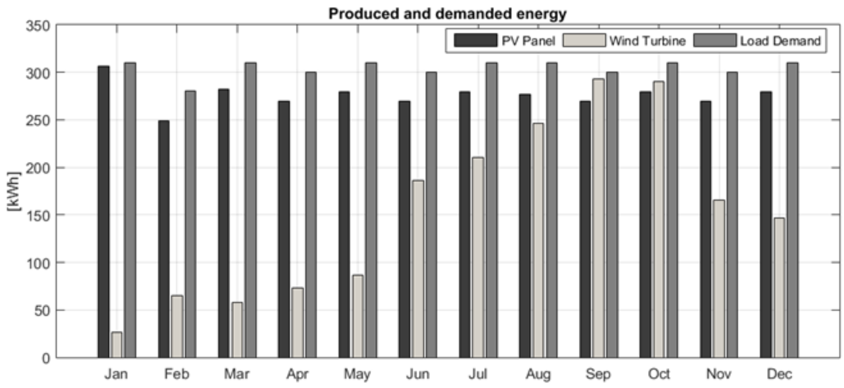

Figure 6- Performance of the most efficient hybrid system for the hypothetical city.

The hybrid system cost for each city is evaluated, since the most efficient systems selected in each case have their differences. Only the initial costs are estimated, neglecting maintenance costs, installation, among others. This estimate is done in two ways: first, if all the equipment is paid immediately (C_{ini}); second, if the equipment is paid over their lifetime (C_{tot}), i.e., in 20 years. In both estimates, it is calculated the cost of the kWh given the total energy demanded along 20 years. For the given generation equipment, it is observed that the cost of Watt per R$ is about seven times larger for a wind turbine, i.e. the cost of photovoltaic energy is about 5.09 R$/W while the wind turbine energy is 34.37 R$/W. Thus, it is expected that the more installed wind power, greater is the system cost, even if wind turbines are more efficient. The hybrid system cost for each case is shown in Tab. 5. Here, the fact that the battery bank must be replaced every three years is neglected, which would affect the cost analysis. An alternative would be to use a battery bank to supply the load demand of the system for just one day, making the system less robust, but reducing the impact in the cost analysis.

In the case of São Martinho da Serra, costs rise because of the need to install a large number of wind turbines. A purely PV system could be an alternative in reducing the cost, the number of panels would increase to 9 and the system efficiency to 16.76%, thus the cost would decrease to R$ 126,345.10. It is observed that due to the significant increase in the monthly average wind speed in the hypothetical city, compared with São Martinho da Serra, the costs are reduced by approximately 60% to an even more efficient system, which shows that the viability of such hybrid system enhances in regions where the energy resource has a well-defined seasonality. In Florianopolis, the selected system has the lowest cost among the three cities observed, since this is only composed of photovoltaic panels.

A further more generalized analysis can be obtained in Fig. 7. There, it is observed that almost all Brazil has a large average availability of solar energy during the year, which means that the use of photovoltaic energy is a good alternative to most of the country. However, the wind potential of the country covers only some specific regions, among these are the south coast and part of the northeastern coast. In addition to these, interior regions also shows good wind potential, where wind speed ranges from 5.21 m/s to 7.64 m/s. Therefore, it is understood that for use of a PV-Wind-Battery hybrid system is necessary to have both good availability of these sources. Another important observation is that the inner regions with better wind potential (inside the northeast and the southeastern part) coincide with those with better solar potential, which enhance the feasibility of using such a hybrid system in those locations. Also noteworthy is that the proposed hybrid system is a good alternative in regions where there is a definite seasonality of available energy from each source, as in the case of the hypothetical city.

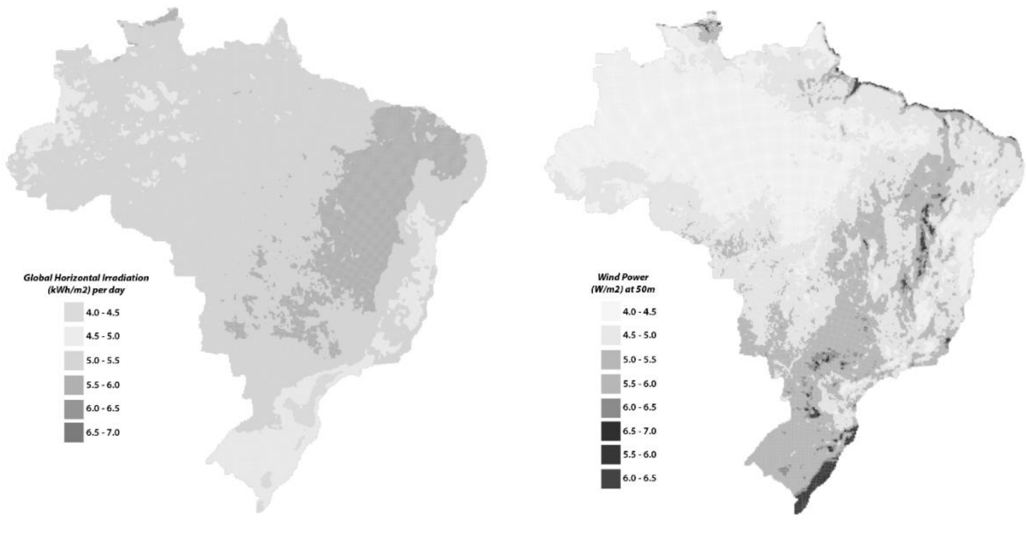

Figure 7- Annual Mean Global Horizontal Irradiation and Wind Power in Brazil (NREL, 2015)

Table 5 – Selected hybrid system costs for different regions of Brazil.

City	C_{tot} ($R\$$)	$R\$/kWh\,[C_{tot}]$	C_{ini} ($R\$$)	$R\$/kWh\,[C_{ini}]$
São Martinho da Serra	271,566.40	3.72	89,931.00	1.23
Florianópolis	126,345.10	1.73	41,840.00	0.57
Hypothetical City	167,706.20	2.30	55,537.00	0.76

4. CONCLUSION

Hybrid systems are a good alternative for energy solutions in Brazil and worldwide. However, the environmental behavior differences in different regions makes the combinations of storage and generation subsystems to be of different types and proportions in each location. In Brazil, it is observed that while for some regions the PV-Battery system shows more viable, in others, the PV-Wind-Battery system is more interesting.

The proposed methodology aims to assess possible hybrid systems for a given region in a simplified manner. Several important factors for an energy project are neglected as losses in cabling, inverters efficiency, the electrical system analysis, dynamic system behavior, the detailed weather behavior, among others. Thus, the values obtained represent only a generalized analysis. It is also important to emphasize that the selected hybrid systems are not optimized systems, but only systems obtained for a first view of their viability. That is, for a design of a hybrid system, other methods must be applied in order to obtain a more detailed analysis and reliable installation.

The cities of São Martinho da Serra and Florianópolis have solar intensity values and wind speeds fairly similar. In both there is more energy available from the sun and low wind speeds in annual average, which leads to use of a hybrid system composed mostly or completely by photovoltaic panels. In the case of the hypothetical city, there is a scene where the monthly average wind speed is far superior to those of previously analyzed cities, so that there is greater feasibility of using a combined PV-Wind generation subsystem, as observed. It is observed that, in general, Brazil has a high availability of solar energy throughout the year. Furthermore, this availability is relatively stable in all months, which means that a PV system will generate electricity with a certain constancy. However, only some regions of Brazil have average wind speed to be sufficient for an efficient generation. This means that there is a greater tendency to use a system composed mostly by photovoltaic panels, as observed in the previous three cities. However, in regions where there is good wind annual average, the hybrid system becomes more efficient, as well as in the hypothetical city, which represents various regions of the country.

Regions where there is a certain weather seasonality, the hybrid system shown most advantageous, if not necessary, since this has the ability of generating electric energy through different sources. So even if at a certain time of year there is low availability of one source, another source can be used to generate. In most cases the cost in R$/kWh performed higher than the national average, which is R$ 0.55. However, for decision-making on the installation of an energy system is not taken into account only the cost but also other factors. The studied hybrid system has several advantages, such as not generating pollution, low maintenance requirements, etc. Moreover, with the development of technology, it is expected that these costs will reduce in the coming years. This system can also be an alternative for use in remote areas of the country, where the cost of installation of electrical networks outweighs the cost of a hybrid system. Therefore, it is concluded that in Brazil there are many locations with high potential for the installation of PV-Wind-Battery hybrid systems, which is showing a relatively efficient system.

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