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TECHNICAL, ECONOMICAL AND ENVIRONMENTAL ANALYSIS OF WIND – SOLAR PHOTOVOLTAIC HYBRID SYSTEM FOR A SMALL COMMUNITY IN FORTALEZA

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Abstract. *Nowadays the use of technologies that do not depend on oil are increasing due to the effects of global warming. Alternative technologies for power plants such as wind turbines and solar photovoltaic panels can contribute to the reduction of emissions. However, it is well known that these types of renewable energy are intermittent. To ensure a constant supply of electricity generated by alternative sources, hybrid systems are being implemented. This paper presents technical, economical and environmental studies of a wind-photovoltaic solar hybrid system to generate electricity for a small community located in the city of Fortaleza, Brazil. The hybrid renewable energy system is connected to the distribution network, without the use of batteries. The payback period is calculated assuming that the wind turbine has two possible lifetimes, 15 and 25 years. The results show that the system can provide electricity for 18 homes. It is economical because the payback period is shorter than the project's lifespan, and produces very low pollution. In fact, the wind turbine is proven to be even more economical and environmentally friendly than solar photovoltaic panels. Finally, the hybrid system is a good alternative to promote the distributed energy generation.*

Keywords: *distributed generation, hybrid system, solar energy, wind energy.*

1. INTRODUCTION

The energy consumption is increasing due to the rise of the population, causing governments to think in enlarging the power plants for electricity generation. Moreover, governments are also concerned by the high use of fossil fuels, which contributes to more contamination. Around the world, governments are creating laws and regulations regarding the protection of the environment and the reduction the use of fossil fuels. Investments in renewable energy projects have been growing. Two of the most implemented alternative energy sources currently are wind and solar PV power. These technologies are being analyzed to improve their energy efficiency, as well as the reduction of their costs of implementation. As it is known, renewable energy sources are intermittent, hybrid systems are compound with two or more renewable or conventional sources of energy to provide electricity to electrical loads as long as possible. In addition, the micro grids are linked to the electricity distribution network to complement the system as energy storage, instead of using batteries, whose use increment investment and maintenance costs.

1.1 Wind Energy

Wind energy is derived from solar energy. Due to different temperatures at the center of the planet and at the poles, caused by different sunlight, it creates the air currents that move from higher temperature places to coldest places, according to Al-Bahadly (2009). Wind power have two energy transformation stage. The first one is the conversion of kinetic energy of wind flows into mechanical energy through the turbine blades, in order to in the second stage by an electric generator converts mechanical energy into electricity. Wind energy is widely available in the world. In addition, this type of energy has significantly less-polluting than a thermoelectric power plant, because it does not produce greenhouse gases in electricity generation or other pollutants.

The production of electricity by wind turbines is highly connected with the speed of the air passing through the blades of it. Equation (1) developed by Freris and Infield (2008) is applied to calculate the electric power generated P by a wind turbine, which is directly proportional to the cube of the wind speed:

$$P = \frac{1}{2}\rho A V^3 C_p \tag{1}$$

Where ρ is the specific mass of air $[kg/m^3]$, A is the cross sectional area of the rotor or effective area $[m^2]$, V is the wind speed $[m/s]$ and the power C_p é coefficient of aerodynamic efficiency of the rotor [%]. As can be seen, wind speed is the most important factor whereby it must be estimated or measured very carefully to minimize the error of the calculation. The cross-sectional area of the rotor is also significant, large rotors for large towers of wind turbines take advantage of the air currents more efficiently than small wind turbines.

There are two types of wind turbines according to its axis, these are horizontal axis and vertical axis turbines. Each has its advantages and disadvantages. The horizontal axis turbines are frequently used in the world, known to have three blades, these are implemented in large-scale projects because they can be used for stronger winds at high altitudes. However, the horizontal axis turbines are difficult to transport and install because of its large size, which must in addition be positioned directly to wind to rotate. On the other hand, the vertical axis turbines are used in medium and small scale applications. They can be installed at ground level and over building roofs and also need not be positioned directly in the wind direction; they can receive air currents rotate in any direction. However, the manufacture of the blades is more complicated due to its shape, which increases production cost.

Depending on the location of the installation, wind turbines can be classified as well. If they are located on the ground, they are known as on-shore or on land or on continent. The other type are the off-shore wind turbines, which are installed in the sea, it is because in the sea, there are more wind resources, which means higher electricity generation. However, it also means a considerable increase in production costs, transportation and deployment.

1.2 Solar Photovoltaic Energy

Solar energy is the largest source of renewable energy. Solar energy is transmitted from the sun by radiation caused by chemical reactions of hydrogen and helium. The solar photovoltaic panels are composed of the union of photovoltaic cells, which through the photovoltaic effect are able to convert directly the photon energy from solar radiation into electricity. Photovoltaic cells are made of semiconductor raw materials with N and P type, which creates an electric field, and with the presence of the energy of photons, do to move the electrons and protons, generating an electric current.

According to Roberts (2012), Eq. (2) shows that the power generated by a series of photovoltaic panels is directly proportional to solar radiation.

$$P = \eta N A I_T \tag{2}$$

Where η is the efficiency of the photovoltaic panel [%], N is the number of photovoltaic panels, A is the area of a photovoltaic panel $[m^2]$, and the solar radiation is I_T $[W/m^2]$. The efficiency of the photovoltaic panel depends on the type and purity of the semiconductor material of this compound. Furthermore, the daylight hours also play an important role in the estimation of the electric power generated by the PV system, these are the times where the panels can generate a considerable amount of energy, and usually engineers take account of 5 to 6 hours of the day sun. For the greatest possible energy, the tilt angle of the PV panels with respect to the surface of the earth has to be chosen according to the latitude of the location (Roberts, 2012).

A photovoltaic system, besides of photovoltaic panels, needs other components to be able to deliver the electricity to devices or loads. There are two possible configurations, the first one is isolated mode, which means that solar system is not connected to the grid so it is mandatory the use of batteries. Because the use of batteries, a charge controller is needed to know how much electricity is generated by photovoltaic panels, to load and unload the batteries in an isolated mode. In grid connected mode, there are no batteries, and the system is directly connected to the utility grid, in this case, surplus energy will be sold to the distribution company, and in case of low generation, electricity is bought from the utility grid, and there is no need of charger controller. The inverter is responsible to convert DC into AC current.

2. SYSTEM DESCRIPTION

In this paper is analyzed a wind-PV hybrid system for an isolated community in Fortaleza - CE with storage batteries that was studied by Matos (2013), from The University of Campinas, making some adaptations. Figure 1 shows the hybrid system to be analyzed, which has a change respect to Matos design, connected to the electricity distribution network to avoid using batteries. The author choose Brazilian wind turbine *Enersud (GRW555)* with 6 kW of power, which is thinking to be installed at 30 meters from the ground. Regarding the photovoltaic panel (PV), the author selected *Yingli Solar* PV with 15.9 % of conversion efficiency and 260 W of power.

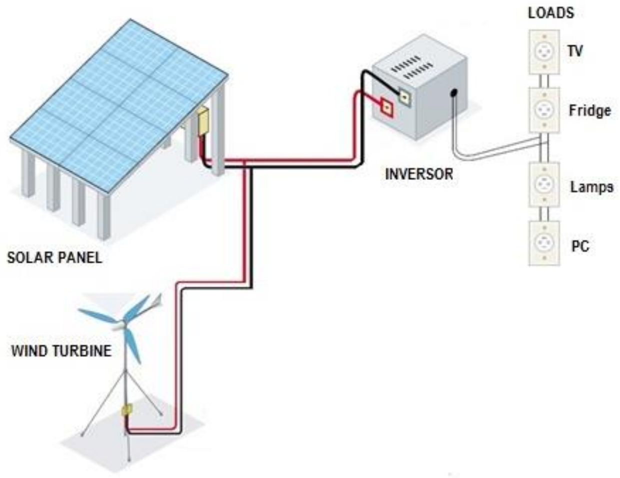

Figure 1. Components of the Hybrid System Wind - Solar Photovoltaic
Source: Adapt from ANEEL Atlas

3. TECHNICAL ANALYSIS

To make the calculations of the electric energy generated by wind energy system and solar photovoltaic system is necessary to collect the wind and solar resources data of Fortaleza. The following graphs show the wind and solar resource potential of the chosen city. According to the Brazilian Wind Atlas, the annual average wind speed at 30 meters height is 4.7 m/s. Table 1 has the means values per month of wind speed at 30 meters of high, the data is taken from *Embrapa* with a historical average, as well as solar data in Fortaleza was taken from solar metric information of *CRESESB*. For the calculations will take the values described in Tab. 1.

Table 1. Average wind speed per month in Fortaleza

Month	Wind speed (*m/s*)	Irradiation daily average monthly (*kWh/m2/day)*
January	4.3	5.20
February	4.2	5.07
March	3.2	4.66
April	3.1	4.58
May	3.8	5.16
June	4.1	5.17
July	4.6	5.88
August	5.4	6.32
September	5.8	6.28
October	5.7	6.39
November	5.6	6.20
December	5.1	5.88
Annual average	4.6	5.57

To continue with the calculations to estimate the electricity generated by the wind turbine to the equation (1) described above, the specific mass of the air ρ in Fortaleza is needed. Applying the study developed by PICARD et al. (2008) from the National Institute of Standards and Technology and with the climatic characteristics of Fortaleza, the specific mass of air (ρ) is 1,153 kg/m3. For the power coefficient C_p of the wind turbine *Enersud GRW555* is calculated with data provided by Matos (2013). Table 2 are the results of calculations of electric power generated by wind turbine in accordance with the speed data described in Table 1.

The month with the highest electricity generation is September with 481.87 kWh, the month with lower generation is April with 73.58 kWh, more than 3 times less than the value of the annual average.

Regarding the solar photovoltaic, solar panels must have a power of 5 kWp (Matos, 2013). Knowing that a *Yingli - Solar* PV panel has a power of 260 Wp, Eq. (3) can give the number of photovoltaic panels (Al-Salaymeh et al., 2010).

$$N = \frac{P_{Sys}}{P_p} \tag{3}$$

Where N is the number of photovoltaic panels, P_{Sys} is the total power of the PV system (W), and P_p is the generated power of one PV module (W). Twenty photovoltaic panels is the quantity of modules to be installed. The dimensions of a photovoltaic panel *Yingli Solar* according to the manufacturer's specifications are 1650 mm x 990 mm x 50 mm, covering an area of 1,634 m^2. In the Tab. 2, it can be observed the results of calculations applying the Eq. (1) and (2) to estimate the generated power by wind turbine and solar panels, as well as the total generated power from the hybrid system.

Table 2. Power generated from wind turbine

Month	Energy produced by wind turbine (kWh)	Energy produced by PV modules (kWh)	Energy produced by hybrid system (kWh)
January	202.91	837.61	1040.52
February	170.78	737.64	908.42
March	83.63	750.63	834.26
April	73.58	713.95	787.52
May	140.04	831.17	971.21
June	170.22	805.92	976.13
July	248.41	947.15	1195.56
August	401.86	1018.02	1419.88
September	481.87	978.95	1460.82
October	472.62	1029.3	1501.92
November	433.72	966.48	1400.20
December	338.53	947.15	1285.68
Monthly average	243.73	880.33	1124.06

The month with the highest electricity generation is October with 1029.30 kWh, and the month with lower generation is April with 713.95 kWh. The hybrid system will generate a monthly average energy of 1124.06 kWh, with a maximum production of electricity in October with 1501.92 kWh.

4. ECONOMICAL ANALYSIS

To make the economical analysis is necessary to know the price of all the components of the hybrid wind- solar photovoltaic system and calculate the cost of investment, maintenance and operation. In table 10, prices of each device is showed, which were consulted on the websites of manufacturers and renewable energy products stores, these are taking into account to meet the total investment. According to Silveira and Gomez (1999), the cost of energy generated C_{ge} is defined in Eq. (4) as follows:

$$C_{ge} = \frac{Inv.f}{H.E_{Sys}} + C_{Ma} + C_{Op} \tag{4}$$

Where Inv is the investment of the plant or project, f is the annual amortization factor [1/year], H is the equivalent period of use [h/year], E_{Sys} is the system power [kW], C_{Ma} is the maintenance cost [US$/kWh], and C_{Op} is the operating cost [US$/kWh]. According to Bollini (2014), the cost of maintenance is the 3% of the investment cost. Due to the type of chosen technologies, photovoltaic solar panels has almost no maintenance, is only the cleaning of the panels, and as the wind turbine, according to the *Enersud* manufacturer, maintenance is minimal as well. However, it is estimate the cost of maintenance regarding Bollini. Operating costs is defined in Eq. (5) taking into account the energy consumed by the complementary components of the hybrid system.

$$C_{Op} = \frac{E_{Inv(cons)}.P_{Elet}}{E_{Sys}} \tag{5}$$

Where $E_{Inv(cons)}$ is the electric power consumed by the inverter [kW], P_{Elet} is the cost of electricity regarding the utility company [US$/kWh]. The annual amortization factor are defined by Eq. (6) and Eq. (7).

$$f = \frac{q^k(q-1)}{q^k - 1} \tag{6}$$

$$q = 1 + \frac{r}{100} \tag{7}$$

Where k is the amortization period in years and r is the annual interest rate [%]. The annual rates of interest that will be considered are 4, 8, and 12 % (BCB, 2013). The operation periods are 1800, 2160, and 7000 h/year. According to *the International Renewable Energy Agency IRENA* (2013), the price of electricity from wind turbines is between 0.05 and 0.17 US$/kWh, and the price of electricity generated by solar panels is between 0.11 and 0.31 US$/kWh.

Table 3. Prices of components of the hybrid system

Component	Amount	Price per unit [US$]	Total Price [US$]
Photovoltaic Panel *Yingli Solar* YL260C-30	20	374.97	7499.56
Wind Turbine *Enersud* GRW555	1	13893.30	13893.30
Schneider Electric inverter XW6048-120/240-60	1	3071.74	3071.74
Installation cost	-	-	2446.40
Total Investment	-	-	26911.00

The total investment of the project is US$ 26911 (Tab. 3). In addition to these costs, it is necessary to know the lifespan of system components and the hybrid system. The lifespan of the turbine is 15 years and the panels is 25 years. Putting the project to have a lifespan of 25 years, means that the wind turbine has to be replaced in the year 15. To calculate the cost of the wind turbine in the year 15, is used the Eq. (8) (Al-Salaymeh et al., 2010).

$$Wind\ \ turbine\ cost\ at\ 15th\ year = \frac{A(1+i)^{N-1}}{(1+d)^N} \tag{8}$$

Where A is the current price of the wind turbine [US$], i is the inflation rate [%], d is the the discount rate of the market [%], N is the number of the year. According to Global-Rates website, the average inflation rate in Brazil for the last 10 years is 5.4 %. Concerning the market discount rate, it is used 6 %. The cost of wind turbine for the year 15 is US$ 12132.9.

Taking into account the price of the wind turbine in 15th year to replace the first one, the total investment is US$ 36597.50 According to ANEEL, the electricity price P_{ele} in the city of Fortaleza is US$ 0.1613 per kWh, from the electricity distribution company of Ceará (COELCE) and the ICMS tax considered is 17% taking from ICMS updated list (2015). Also according to COELCE (2013) and the considerations of Matos (2013), the average monthly consumption for a new connection (Small Basic House) is 60 kWh according to the Light for All Program LPT. With an average monthly generation of 1124.06 kWh of electricity, the hybrid system can provide electricity to 18 new homes. In a full year, the system will generate 13782.12 kWh, which means that the annual cost of electricity is US$ 2678.40. The payback period is the time in years it takes to recover the initial investment in the project. To calculate the annual revenue, the Eq. (9) is defined:

$$Anual\ Revenue = Inv - (H.E_{Sys}.P_{ele}) \tag{9}$$

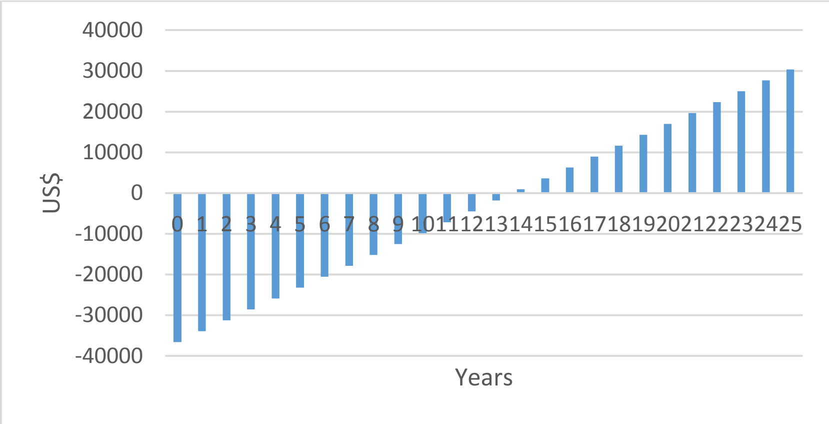

Figure 2. Annual revenue from electricity generation with the hybrid system with a useful lifespan of 15 years for the wind turbine.

In Figure 2 is observed the payback period with the parameters described above is 14 years. Nevertheless, according to studies presented by Ahmed and Cameron (2014), a wind turbine service lifespan can reach 25 years up to 30 years, while the project investment cost would be US$ 26911, and the payback period would be 10 years.

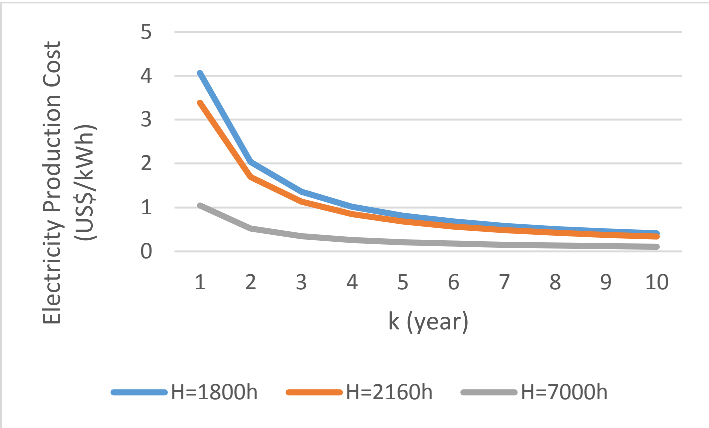

Figure 3. Electricity production costs by the hybrid system according payback (r = 8%)

According to Figure 3, by fixing the interest rate at 8 %, it is observed that for the wind-solar photovoltaic hybrid system, electricity production costs for the period of operation of 1800 h/year started in the first year with US$ 5.1267/kWh and in the ninth year in US$ 0.5716/kWh. For the period of operation of 2160 h/year in the first year, the cost is US$ 4.2723/kWh and in the ninth year in US$ 0.4764/kWh. The operation period of 7000 h/year in the first year began with US$ 1.3185/kWh and in the ninth year is US$ 0.1472/kWh.

5. ENVIRONMENTAL ANALYSIS

The environmental impact is very significant at design stage of the project to know if it is whether viable or not as well as to fulfill with the environmental regulations. Pollution issues have done that governments create laws and regulations to reduce pollutant gases and greenhouse gases in the air. The main greenhouse gas emissions are Carbon dioxide CO_2, Sulfuric dioxide SO_2, Nitrogen oxides NO_X and Particulate Matter MP.

According to Cardu (1999) and Baica (2001), the ecological efficiency evaluates how polluting is a thermoelectric plant, considering the combustion of 1 kg of fuel, not the amount of gases released per unit of energy generated. The CO_2 $[kg/kg_c]$ equivalent is described by the following equations:

$$(CO_2)_e = CO_2 + (SO_2)_e + (NO_X)_e + (MP)_e \tag{10}$$

$$(CO_2)_e = CO_2 + 80(SO_2) + 50(NO_X) + 67(MP) \tag{11}$$

According Villela (2007), the ecologic efficiency is a dimensionless indicator to assess the environmental impact of exhaust emissions from a thermal power plant, by comparing integrated pollutant emissions hypothetically (equivalent emissions of CO_2) with existing standards air quality. Equation (12) is the definition of ecological efficiency regarding Bollini (2014):

$$\varepsilon = \left[\frac{0{,}204\eta_p}{\eta_p + \Pi_g} In(135 - \Pi_g)\right]^{0{,}5} \tag{12}$$

Where ε is the ecological efficiency [%], η_p is the efficiency of the technology [%] and Π_g is the pollution index $[kg/MJ]$. The value of ecological efficiency is within the range 0-1. When ε is zero, the system is very polluting and when ε is equal to one, the system has no pollution. The critical value of eco-efficiency is 0.5. The pollution indicator is defined as follows (Bollini, 2014):

$$\Pi_g = \frac{(CO_2)_e}{Q_i} \tag{13}$$

Where Q_i is the lower calorific value of the fuel PCI $[MJ/kg]$. However, in this case, the hybrid system will not use a fuel to generate electricity. Wind and solar PV energy use the natural resources that are present in the city of Fortaleza. Thus, the pollution indicator Π_g is taking from Global Warning Potential (GWP) indicator, which considers the *LCA (Life Cycle Assessment)*. LCA quantifies the ecological impact of production and implementation of a type of technology. According Turconi et al. (2013), the GWP indicator for wind turbines is $0.0153\ kg(CO_2)_e/kWh$ or $0.00425\ kg(CO_2)_e/MJ$. The GWP indicator for solar photovoltaic panels is $0.052\ kg(CO_2)_e/kWh$ or $0.0144\ kg(CO_2)_e/MJ$. With wind turbine efficiency of 25 % and solar photovoltaic panels' efficiency of 15.9 %, ecological efficiency is 99.2 % and 95.8 % respectively. This means that the wind system is less polluting than the solar photovoltaic. Nevertheless, both renewable energy sources have a good ecological efficiency, there cannot be consider free pollutants because manufacturing and logistic stages use fossil fuels.

6. CONCLUSION

Due to renewable sources are intermittent, hybrid systems can be a good alternative to generate electricity for buildings and communities, ensuring that electricity is supplied constantly.

This paper makes a technical, economical and environmental analysis of a wind - solar photovoltaic hybrid system for a community in the city of Fortaleza in the state of Ceará, which was studied by Matos (2013). Wind and solar resources data of Fortaleza were obtained from *Embrapa* and *CRESESB* companies respectively, these were taken into account to estimate the energy generated by the hybrid system. The components of hybrid system chosen were a Brazilian wind turbine and Chinese solar photovoltaic panels. The wind- solar photovoltaic hybrid system can generate an average annual energy of 1124.06 kWh, which can provide electricity to eighteen small basic homes in the community.

The initial investment of such systems is high, but the hybrid system is designed to operate for 25 years. The lifespan of wind turbine is 15 years and for solar photovoltaic panels is 25 years. Annual inflation is estimated at 5.417 %, taking into account an inflation history of the last 10 years. The payback period is 14 years. Nevertheless, the lifespan of a wind turbine, according to studies can reach 25 years, reducing the payback period to 10 years. The cost of electricity generation by the hybrid system is lower if the interest rate is low. In addition, when the plant has more hours of operation, low cost significantly. Moreover, government subsidies is not taking into account in this study. With subsidies, payback period can be reduced more.

Having regarded to the GWP indicator of each technology (wind and solar photovoltaic energy), the ecological efficiency for wind turbine is 99.2 %, and for the solar photovoltaic is 95.8 %. Wind energy is more efficient ecologically the lowest contaminant that the solar photovoltaic. However, the hybrid system has a high environmental efficiency.

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