Energetic Efficiency of Self-renewable Alternative Sources for the Generation of Electrical Energy

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ABSTRACT

Mankind has increasingly used fossil fuels to meet the high demand for power. In order to build a sustainable energy system, one must consider the use of self-renewing resources such as the sun, wind, water, earth and plants. Energy efficiency from self-renewing resources were analysed in the laboratory and the results obtained were compared with those form the literature, although each of the renewable energy technologies are in a different stage of research, development, and commercialization. The alternative energy sources analysed exhibited good energy efficiency performance. For instance, the hydrogen cell achieved an efficiency of approximately 50%, compared to 75% to 85% of efficiency found in the literature. The wind energy efficiency generator generally stood at 12%, being the theoretical efficiency found in the literature of 15% to 35%. The photovoltaic panel energy efficiency was 11.6%, as the reference parameters are around 14% to 16%. When compared to results obtained with large scale equipment, the results are different. The determination of renewable potentials and their uses is one of the aims in maintaining sustainable energy generation.

Keywords: *Energetics Efficient; Environment; Clean Energy; Generation.*

1. INTROCTION

The global climate change raises concerns. The increasing demand for electricity shows that emissions of greenhouse gases, caused mainly by burning fossil fuels, will also increase. Therefore, effective actions become necessary in order to reduce their emissions (Hosenuzzaman et al., 2015).

The development of the global energy industry must search for security of supply and meet energy demand for the purpose of taking a path towards environmental and economic sustainability. In this scenario, new methods of using natural resources were developed, leading to the expansion of renewable and clean energy sources (Roy and Das, 2017). Among the alternative sources of generation of electricity are wind energy, solar energy and hydrogen cells (ANEEL, 2018).

Wind energy was one of the first alternative sources of renewable energy used by man. By definition, it is the kinetic energy of the flowing air mass, which converts the mechanical energy into electrical energy using a generator (Chen et al., 2014).

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Solar energy is generated by the direct conversion of light into electricity from a device made of semiconductor material. Photovoltaic cells, which constitutes the photovoltaic panel, were developed in 1954 by Bell Laboratories researchers. The panels, mostly made of Silicon (mono and polycrystalline), work by capturing the electromagnetic waves coming from the solar irradiation (Santos, 2016).

The electric energy from hydrogen is generated from fuel cells that are basically batteries and, that through electrochemical processes, converts the chemical energy of a fuel into electricity (Andrade, 2003) (Aldabó, 2012).

The most recent data show that only 13% of electricity generation comes from renewable sources: 10% is energy generated from biofuels and industrial waste, 2.3% from water resources and 0.9% from the generation cluster involving solar, wind, geothermal and hydrogen cells (Hosenuzzaman et al., 2015) (Roy and Das, 2017).

Thus, preserving ecosystems and reducing greenhouse gases, i.e., preserving the environment in such a way that electricity generation has a minimally tolerable impact is of great importance for future generations. Even with small-scale use, the study to improve the efficiency of alternative forms of electric power generation emerges as a baseline ally for effective, safe and highly non-polluting sources (Roy and Das, 2017) (White, 2004).

The purpose of this paper is to compare data obtained from the laboratory with the most recent data found in the literature on energy efficiency. Moreover, it aims to make reflections by simply quantifying the energy efficiency of alternative sources studied for future research applications.

It is an initial study and guideline for future research and improvements regarding the efficiency of systems as well as for each alternative source of electric energy being compared. In addition, greenhouse gas emissions indicate the necessity of investing in alternatives proven viable (Payam et al., 2015). In this context, generating systems from non-polluting inputs are presented as environmentally acceptable alternatives and with good energy efficiency (Herrero et al., 2016).

2. MATHEMATICAL METHOD FOR ENERGETICS EFFICIENCY

2.1 Photovoltaic Solar Panel

The way to harness solar radiation is through solar cells, or photovoltaic systems. Solar cells are electronic components that convert the energy of solar radiation into electricity by moving the photons (Santos, 2016). Therefore, the efficiency of the photovoltaic panel demonstrates the amount of incident radiant power that can be converted into electric energy, as shown in **Equation 1** (Santos, 2016).

$$\varepsilon_S = \frac{P_S}{P_e} \tag{1}$$

The ratio between P_e and P_s is the efficiency of the solar cell ε_s, which are the power of the solar energy and the output power respectively.

The photovoltaic panel use, as show the **Figure 1,** for energy efficiency estimation has four modules of polycrystalline silicon solar cells, each module with 26 mm × 77 mm, giving a total area of 8×10^{-3} m^2. The tests were based on the pattern conditions of 1000 W/m^2 at 25 °C.

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Figure 1. Photovoltaic panel.

This test condition is regulated by ASTM standard E-1036, better known as standard test conditions for irradiance and temperature of the cells of the photovoltaic module (NBR11879 / EB2179, 1991). For the statistical distribution, ASTME-891 and E-892 were used and the Brazilian standard (BR12136 / MB3477, 1991) was used for the other tests.

2.2 Wind Power Generators

Wind generators or wind turbines are machines capable of converting kinetic energy from the winds into electrical energy. The kinetic energy is generated by the wind originated from the heating of the terrestrial surface (Miller, 2008).

The energy generated can be transferred directly into the grid, usually when it's generated by large wind turbines or in isolated systems for small systems (Aldabó, 2012).

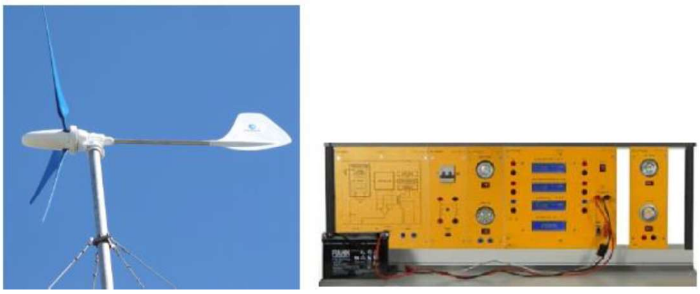
Energy efficiency is calculated by the amount of power available in the wind that can be used and, therefore, converted to mechanical power, as shown in **Equation 2** (Custódio, 2009).

$$\varepsilon_e = \frac{P_t}{P_v} \qquad (2)$$

Where ε_e is the wind cell efficiency, defined as the ratio between P_t and P_v, which are the power extracted from the turbine and the available wind power, respectively (Custódio, 2009).

The energy efficiency of wind generation was based on a small *ENERSUD – Gerar 164* system, which contained three active stall control blades, 1.64 m rotor, with 400 W and 500 W nominal and maximum power, respectively, as show the **Figure 2**. The nominal velocity was 12.5 m/s, the starting velocity was 2.2 m/s and the maximum power velocity was 20 m/s, the wind turbine was installed 4 m from the ground.

Figure 2. Wind power generation ENERSUD – Gerar 164 system.



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The choice of the turbine composed of three blades is due to its more stable and better distributed stresses during the rotation of the machine to follow the direction of the wind (Dutra, 2007).

2.3 Hydrogen Cells

Hydrogen cells are classified by the operation temperature, which is intrinsic to the electrolyte used in such electrochemical reactions. In order to perform the energy efficiency calculations, PEM-type hydrogen cells with proton exchange membranes were used, as show the **Figure 3**. The proton exchange membrane is made of plastic and solid material, capable of carrying positive charges when it is moist. It works on temperature around 60 ºC to 140 ºC (Serpa, 2004).

Figure 3. PEM-type hydrogen cells with proton exchange membranes.

The maximum volume of hydrogen produced by the system was used for the measurements, which corresponds to 30 cm^3. Time was measured in increments of 5 cm^3 of gas consumed. The theoretical efficiency percentage of steam turbines and similar devices is intrinsically limited by the nature of the process and can be calculated by **Equation 3** (Andrade, 2003) (Sorensen and Spazzafum, 2018).

$$\varepsilon(\%) = \frac{T_1 - T_2}{T_1} x 100\% \quad (3)$$

Where T_1 is the inlet vapor temperature and T_2 is the outlet vapor temperature. For a hydrogen cell, or cell-to-fuel, hydrogen and oxygen inside the cell react to produce water, releasing heat and electricity in the process.

Therefore, the maximum theoretical efficiency expected for a hydrogen cell is the conversion of approximately 50% of the incoming hydrogen into electrical energy. Effects on heat transport and mechanical friction result in a lower practical efficiency value (Sorensen and Spazzafum, 2018) (Bribián, 2005).

The total energy released in a chemical reaction and the maximum useful work that can be obtained relates to the enthalpy change (ΔH), which is the total energy released, and the Gibbs energy variation of the reaction (ΔG), which is the energy available to perform work, as shown in **Equation 4** (Bribián, 2005) (Larminie, 2002).

$$\varepsilon_H = \frac{\Delta G}{\Delta H} \quad (4)$$

Where ε_H is the fraction of the chemical energy of the reactants that is converted into electrical energy, which is the thermodynamic efficiency of the electrochemical conversion in the cell (Larminie, 2002).

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3. RESULTS E DISCUSSIONS

To measure the intensity of the radiation incident on the photovoltaic panel, a pyranometer was used. To estimate the power, a multimeter was used, since the short-circuit current (maximum photoelectric current) is proportional to the photons (radiation) that reach the photovoltaic plate. The short-circuit current is therefore proportional to the incident radiant power of light. The open circuit voltage depends on the semiconductor material of which the solar cell is made.

The maximum irradiance of a very sunny days is about 1000 W/m^2. The characteristic of the photovoltaic panel was based on the standard test conditions described. The maximum short-circuit current was 600 mA under standard test conditions. Thus, the correct measurement of incident solar energy per unit area was obtained which was approximately 1.67 W/m^{2}mA. **Figures 4** and **5** show the graphs of the characteristic curves obtained from the collected data.

Analyzing the graphs, the maximum electric power generation point (MPP) is the product of the voltage and the energy are larger, in this case, the value of P_{out} is 0.311 W, the same as that of the P_{MPP}. From **Equation 1** has been observed that the maximum energy efficiency of the photovoltaic panel is 11.6%. Measurement errors and inaccuracies in determining the incident radiant power should be considered. In addition, the efficiency of the photovoltaic board is less than the efficiency of individual solar cells. This is caused because not all solar cells have identical properties.

Figure 4. Graph of current versus voltage.

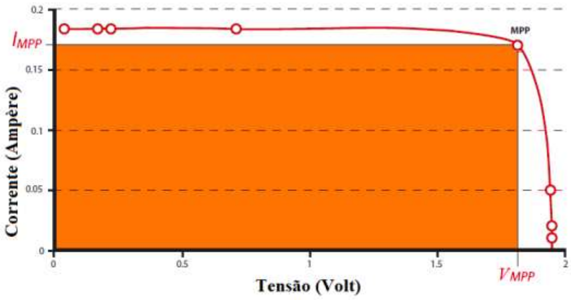
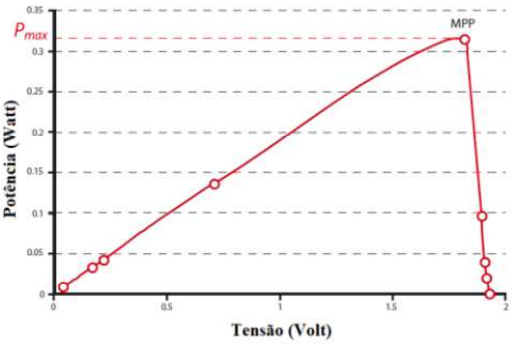


Figure 5. Graph of power versus voltage.



According to the Brazilian Wind Energy Association (ABEEólica, 2018), wind energy currently accounts for 5.4% of Brazil's installed electricity generation capacity, enough to cover residential consumption in a region of 30 million inhabitants. The share of the wind power source in the Brazilian energy matrix is expected to be 12% in 2020.

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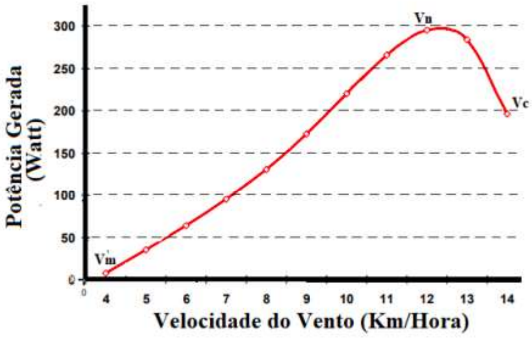
The power of a wind turbine varies with wind speed and each wind turbine has a characteristic curve of energy performance (Miller, 2008). With this curve it is possible to predict the energy output of a wind turbine without considering the technical details of its various components.

Thus, the power curve of the wind turbine is shown in the graph of **Figure 6**, where the point of the maximum production of electric energy at different wind speeds is indicated. The graph shows three important points for the turbine performance analysis: the minimum speed (V_m), the nominal speed (V_n) and the cutting speed (V_c).

Figure 6. Graph of the power created versus wind speed.

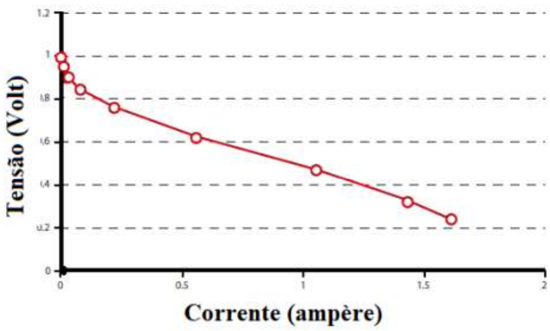


By definition, the minimum speed is the wind speed at which the turbine starts to generate energy. The nominal speed is the wind speed at which the wind turbine reaches its nominal energy (this often means its maximum power). Finally, the shear rate is the wind speed at which the wind turbine shuts off to prevent generator power from working at harmful levels (Custódio, 2009) (Dutra, 2007).

Measurements were made over a period of three months and from **Equation 2**, the determined efficiency of the system was an average of 12%. This value disregards the differences that are caused due to the location of the system. It was observed that when comparing to the data, for all analysed months, the value obtained is lower than those found in the literature that is around 15 to 35% (Amaral, 2011).

For the measurements and calculations of the energy efficiency of the hydrogen cell, the maximum volume of hydrogen was produced for the system in use, which corresponds to 30 cm^3. From the system switch on, time was clocked in constant volume increments of 5 cm^3 of consumed gas. The graphs of the generated characteristic curves are shown in **Figures 7** and **8**. The graph of **Figure 7** shows the characteristic curve of the voltage in volts and the ampere current generated by the hydrogen cell.

Figure 7. Graph of voltage versus current.



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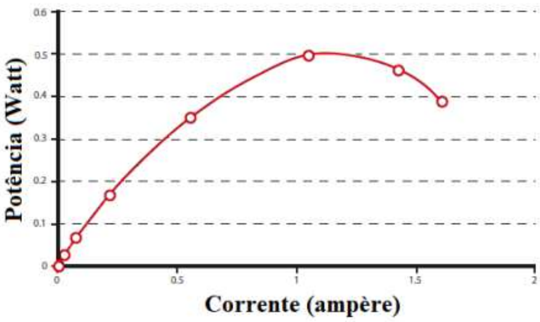
Note that the current is inversely proportional to the voltage, i.e., the higher the current, the lower the system output voltage. The graph of **Figure 8** shows the characteristic curve of the power and current generated by the hydrogen cell.

Figure 5. Graph of power versus current.



The current in which the fuel cell reaches the highest output power at 1.05 A, as shown in the graph of **Figure 8**, which corresponds to a load resistance of 0.33 Ω. It was noted that the hydrogen gas that is introduced into the cell is continuously converted into electrical energy. The time, voltage and current values were recorded in **Table I**, for the specific volumes (in increments of 5 cm^3 of consumed hydrogen gas).

Table 1. Gas Volume in the Tank and Hydrogen Consumption in Relation to Time.

Number of Measures	Hydrogen Volume (cm3)	Time (t/s)
1	30	0
2	25	175
3	20	356
4	15	534
5	10	712
Voltage (V)	**Current (A)**	**Power (W)**
0,73	0,22	0,16
0,72	0,21	0,15
0,72	0,21	0,15
0,71	0,21	0,14
0,72	0,20	0,14
V ± 0,72V	A ± 0,21 A	P ± 0,15 W

The energy efficiency of the fuel cell in the experiment according to **Equations 3** and **4** was 50%. This means that 50% of the stored energy produced by the hydrogen gas is used in the operating cell system, the other 50% is available to be used.

The electrolyte depends on the power level, just like the cell. Despite the higher cell efficiency, if the charge has a high electrical resistance, which only operates partially, the energy produced is, therefore, less than it could possibly produce.

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4. CONCLUSION

The initial aim of the research was to provide energy efficiency data from the three most widely used types of alternative sources of renewable energy: hydrogen cells, photovoltaic solar panels and wind turbine prototypes, through experiments and data collection.

The fuel cell is an important technology with major breakthroughs in the energy, transportation and entertainment sectors around the world. It's a technology that uses hydrogen and oxygen to generate electricity with high efficiency and with zero or low emissions of pollutants. Hydrogen can be obtained from a variety of energy sources, such as: ethanol, natural gas, biodiesel, biogas, water, glycerol, solar, wind, hydro, nuclear, etc. (Chum, 2002) (Bribían, 2005) (Hosenuzza-man et al., 2015).

The hydrogen cell that was analyzed has an energy efficiency of approximately 50%, i.e., half of the energy produced was used by the system and the other half was generated to be used. Commercially available large energy PEM type cells have an energy efficiency average of 75% to 85%.

In the comparison between the energy contained in the wind and the one supplied by the wind turbine, the analyzed wind generator presented an energy efficiency of approximately 12%, according to the measurements made.

It is important to note that the project assembled for this analysis disregarded a previous study to optimize its location. Its main objective was to carry out the first analysis of wind regime, measurements and familiarization with the technology of wind generation. This efficiency value is below, as could be expected, from those found in large-scale commercial wind farms, which are around 15% to 35% (Amaral, 2011).

Photovoltaic solar energy will receive incentives in Brazil for the installation of solar power plants for electricity production, as well as factories for solar panels. In the system under study the maximum energy efficiency of the photovoltaic panel was 11.6%. In comparison to the efficiency of commercially available polycrystalline photovoltaic panels having an efficiency ranging from 14% to 16%, the system under study was not so discrepant (Santos, 2016).

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