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Hydro, thermal and photovoltaic power plants: A comparison between electric power generation, environmental impacts and CO_2 emissions in the Brazilian scenario

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Abstract
The challenge of sustainability is present in electricity generation. The sources should be renewable, and production should respect the environment and all forms of life. Being the main energy sources in Brazil, hydroelectric and thermal power plants have drawbacks when considering environmental impacts. In contrast, the use of photovoltaic energy is a sustainable alternative, pollution-free in its operating phase and with significantly less impact in its construction phase. The purpose of this article is to make a relation between the electricity generated by the hydroelectric Itaipu plant, the thermoelectric complex Jorge Lacerda, the Eletronuclear plant, and the analysis of a photovoltaic plant proposal for these three scenarios. The relation between the production of electricity in Itaipu, Jorge Lacerda, and Eletronuclear power plants, and the projected energy production of a photovoltaic plant for each scenario was obtained through calculations according to the area of each plant, generating a comparison between the installed power of the referred plants, and the estimated installed capacity for the projected photovoltaic plant. The environmental impacts were assessed for the different scenarios, and CO_2 emissions were quantified. The calculated results show that the installed power of the projected photovoltaic plant was significantly higher than the installed power of the existing plants. The photovoltaic plant's capacity factor, for the proposed study, was of 15%, and the projected annual photovoltaic energy for the respective areas presented significantly higher values, of approximately 330,180.40 TWh in comparison to Itaipu plant, while in comparison to Jorge Lacerda plant, for instance, it was of approximately 428,229.23 TWh, whereas to Eletronuclear it was 0.0288 TWh. The results of this study show that photovoltaic plants with equivalent areas of Itaipu and Jorge Lacerda power plants, could generate higher annual energy, nevertheless the same analyses to Eletronuclear power plant showed that the projection would not be viable.

Keywords: Sustainability; Energy; Power plants; Photovoltaic generation; Energy matrix.

1. Introduction

Sustainability is a concept which states the preservation of a system where the needs are met, resources are exploited consciously, and future generations are not compromised. To consider something sustainable, it is necessary to analyze the current need, as well as draw a projection of future need, relating this to the way the resources were used in the past, how they are being used now and how they will be used in the future [1].

This concept is based on a scenario where the needs will increase, and resources will be required to be used with intelligence and a sense of preservation in order to maintain uninterrupted supply of needs. "It is the development that meets current needs without compromising the ability of future generations to meet their own needs" [2].

Considering the aspects involved in the maintenance and development of human life, we observe that energy is a key factor of all the efforts made to achieve sustainable development. Energy is essential to eradicate poverty, increase human well-being and raise living standards [3].

The electricity generation, therefore, faces the challenge of sustainability, where there is a constantly growing demand. The sources should be renewable, and production should respect the environment and living beings. According to the United Nations, in the implementation plan developed in the 2002 World Summit on Sustainable Development in Johannesburg, one of the goals is taking actions in pursuit of economically viable energy production, socially acceptable, coming from sustainable sources. This shows how important it is to diversify energy matrices [4].

Bringing this challenge to the Brazilian reality, it must be analyzed what are the energy sources used, what are the impacts caused by them, and what are the alternative sources that fall under the sustainable premise.

The biggest source of electricity in Brazil are hydroelectric power plants, which have a large power generation capacity. This energy source represents more than 60% of the national installed capacity [5]. The Itaipu plant, built partially in the city of Foz do Iguaçu, Brazil, and partially in Hernandarias, Paraguay, is Brazil's largest hydroelectric plant, with a power generation capacity of 14 GW (gigawatts), in an area of 1,350 square kilometers, according with the National Electric Energy Agency [6] (Figure 1).

Figure 1. Itaipu power plant' view [7].

The construction of a hydroelectric power plant demands a long time and affects the geology and geomorphology of the site, through silting, breaking and intensification of erosion; hydrology, resulting from large areas of flood and dam construction; fauna and flora, and also the socio-economic environment due to the possible removal of urban centers. Experts say that the flooding of large areas covered by vegetation has a direct impact on the local climate and can contribute to global climate change through the increase of greenhouse gases in the atmosphere [8].

Therefore, although it is the main energy source in Brazil, hydroelectric plants have drawbacks when examined through the sustainable perspective.

The second largest source of electricity in the country are the thermoelectric plants. These use fuels from different sources: gas, biomass, diesel / fuel, mineral coal and nuclear. This represents 28% of the installed capacity in Brazil [5]. Among these plants, we can mention the Jorge Lacerda complex.

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According to data reported by Tractebel, the Jorge Lacerda Complex is located in Capivari de Baixo, Santa Catarina state (Figure 2). The complex consists of five plants, which occupie an area of 2,000 square kilometers, with a total installed capacity of 857 MW (megawatts), and a capacity factor of about 60%, enough to supply a city of 4 million inhabitants. The electricity capacity factor is the ratio of the plant's production over a period of time and the maximum total capacity during the same period [9].

Figure 2. Jorge Lacerda Complex’ view [10].

Coal plants, such as Jorge Lacerda, are large emitters of greenhouse gases and acid rain, due to the burning of fossil fuels, where the discharge of hot water into the environment occurs. Studies conducted in the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE) point out that a thermal plant is more harmful to the environment that a hydroelectric. "The thermal plant not only emits hot gases, but also sulfur and nitrogen biocides, as well as particular materials, highly harmful to human health." The pollution causes respiratory problems such as infections of the bronchi and lung diseases [11].

Nuclear power plants are considered to be in the same category of thermoelectric power plants, and they contribute to the national energy matrix. They represent 1.32% of Brazil's installed capacity [5]. The unit of Angra 2, the largest plant of its kind in operation in the country, has a rated power of 1,350 MW with a predicted capacity factor of 90.14% (ANEEL, 2016). Located in Angra dos Reis, in the state of Rio de Janeiro, Angra 2 is one of the two operating nuclear power plants in Brazil, the other being Angra 1. Together, they form the Eletronuclear facilty, which covers an area of 0,131 square kilometers, and has an installed capacity of 1,990 MW [12] (Figure 3).

Figure 3. Eletronuclear power plant’ view [13].

As well as the hydroelectric, thermoelectric power plants present negative factors regarding the preservation of the environment, one of the main pillars of sustainability.

The wind farms are clean alternative sources, which have shown tremendous growth in the Brazilian energy matrix. In the first half of 2015, the average generation was 1,831 MW. In the same period of the previous year, the average generation was 856 MW [14]. The installed capacity today is 8.12 GW, obtained from 322 mills [15].

As a highlight, we have the Geribatu wind farm, with an installed capacity of 258 MW, serving 1.5 million people. The park consists of 129 wind turbines [16]. Located in Santa Vitória do Palmar, in the extreme south of Rio Grande do Sul state, the park occupies an area of 48 square kilometers [17] (Figure 4). Because Geribatu started operating recently, it will not be considered for projection comparison.

Figure 4. Geribatu wind plant' view [17].

Another alternative source, and focus of this article, photovoltaic energy is a sustainable alternative, pollution-free in its operation phase and with significantly less impact in its construction phase. This energy source is still little representative, with its installed capacity accounting for 0.0144% of the Brazilian energy matrix, with 26 solar generating power plants, with a capacity of 21,263 kW (kilowatts), an insignificant amount compared to its potential [5].

The biggest photovoltaic power plant in Brazil is the Cidade Azul power plant, also known as Nova Aurora (Figure 5). It is located in the city of Tubarão, Santa Catarina state, and has an installed power capacity of 3 MW, using different technologies on its photovoltaic modules, being part of a research project serving as an implantation model of solar energy in Brazil [10].

Figure 5. Cidade Azul photovoltaic power plant's view.

The photovoltaic modules, a key component of the grid connected system of photovoltaic energy, consists of photovoltaic solar cells, which mainly use the monocrystalline silicon material (m-Si) and polycrystalline (p-Si), which uses relatively thick crystalline blades [18]. These types of cells represent the majority of world production, and the recycling process of both types are through pyrolysis [19].
Another major component of the system, the photovoltaic inverter, has the function of converting the direct current which is supplied by the PV generator, into a alternated current; and convert the voltage of the photovoltaic generator to the same voltage range existing on the local electric grid [20].
One of the problems for the development of photovoltaic energy on a large scale, are the high cost of equipment for the implementation, as the majority is obtained through imports; the lack of awareness of the improvements that a clean and renewable source provides and the lack of incentives of public policies to promote the integration of the generated energy in the electrification network companies.
The construction of a photovoltaic power plant would require a large area, causing similar impacts caused by the hydroelectric and thermoelectric plants. However, the photovoltaic system, unlike any other energy source, can be installed in existing areas, such as facades and roofs. The modification of the urban setting, with the accession of photovoltaic modules, is a much lower social and environmental impact than that caused by hydroelectric and thermoelectric plants.
The purpose of this article is to make a relation between electricity production generated by the Itaipu plant, the thermoelectric Jorge Lacerda complex, the Eletronuclear plant, and the projection of a photovoltaic plant for each scenario, considering the area and the capacity factor of each plant and comparing the environmental impacts caused by them.

2. Material and methods

The relationship between the production of electricity in Itaipu, Jorge Lacerda, Eletronuclear power plants, and the projection of a photovoltaic power plant for those different scenarios were obtained by calculations according to the area of each plant, generating a comparison between the installed power of the plants mentioned and the estimated installed capacity for the projected photovoltaic power plants.
For photovoltaic power calculation purposes, it was used a module with an output of 310 Wp (Watt-peak, unit for peak power achieved by photovoltaic modules under standard conditions) and an area of 1.95 m², and to calculate the number of modules, equation 1 was applied for both cases [21].

$$N\,\mathrm{mod} = \frac{Area\,available}{Area\,\mathrm{mod}\,ule} \tag{1}$$

where Nmod is number of modules, Areaavailable is area which each plant occupies and Areamod is area of each photovoltaic module.

The result obtained on the number of modules, it is possible to calculate the estimated installed capacity based on the areas of each compared plant [21]. In equation 2, it is obtained the installed photovoltaic power, wherein the power of each module is multiplied by the number of modules, resulting in the total installed photovoltaic power [21].

$$Ppv = P\,\mathrm{mod} \times N\,\mathrm{mod} \tag{2}$$

where Ppv is total installed photovoltaic power, Pmod is power of each module and Nmod is number of modules.

The results obtained by Equation 2 reflect the power installed for each projected photovoltaic power plant, however it should be taken into account the capacity factor for each plant, because it is their actual capacity to generate power, in relation to the power that the plant would generate if it operated at rated power for 24 hours a day during the year [22]. Equation 3 represents the quantity in question.

$$CF = \frac{E}{Ppv \times 8760} \tag{3}$$

where CF is capacity factor %, E is generated energy annual (kWh/year), Ppv is total installed photovoltaic power and 8760 is the total amount of hours within an year.

Calculation of annual energy for each projected photovoltaic plant, taking into account each area, is obtained through the equation 4 [23].

$$E = \frac{Ppv \times Htot \times PR}{G} \times 365 \tag{4}$$

where E is the annual energy to be generated (kWh / day), Htot is the incident solar irradiation at the photovoltaic modules plane (kWh / m².day), PR is the Performance Ratio (typically between 70% to 80%), G is the irradiance at STC (standart) conditions (1,000W / m²) and 365 is the total amount of days within an year.

Regarding the value of the Htot, it will be used the value of the incident solar irradiation in the inclined plane of each plant, according to the latitude of each local. As a result, the average annual Htot values presented for the cities of Foz do Iguaçu, Parana state, Capivari de Baixo, Santa Catarina state, and Angra dos Reis, Rio de Janeiro state, will be collected from the Brazilian atlas of solar energy [24].
The performance ratio considered for this study will be 75%, value typically used in the development of photovoltaic systems [25].
The environmental impacts are assessed for the different scenarios in order to assess the direct and indirect influences acting on the environment, and consequently point sustainability conditions in the operating phases for each studied plant.
Finally, CO2 emissions are quantified by through the annual reports of each plant along with the appropriate literature for comparison purposes between these traditional plants and photovoltaic plants.

3. Results and discussion
The comparison between hydroelectric, thermoelectric, nuclear and photovoltaic power generation is shown in Table 1. As the area of each plant, according to the annual report of each plant, where Itaipu has a 1,350 square kilometers [7], considering the reservoir area, Jorge Lacerda a total area of 2,000 square kilometers [10], and Eletronuclear 0.131 square kilometers approximately [13]. It was possible, using the equations 1 and 2 contained in the methods section, to estimate the PV installed capacity for photovoltaic plants with the same respective area.
According to the Brazilian atlas of solar energy [24] it is possible to collect the H_{tot} for the locations where the power plants are located. The Htot values were 5.62, 4.92 and 5.03 kWh/m².day to Itaipu, Jorge Lacerda and Eletronuclear respectively. These values were applied in photovoltaic annual energy calculation (equation 4) as shown in Table 1.
It is important to highlight that the metal structure, which supports the modules, common in photovoltaic facilities, as well as the spacings between the modules were not considered, due to the fact that the power capacity and the energy are the focus of this study. Thus the results of the calculations of the equations 2, 3 and 4 are presented in Table 1.

Table 1. Comparison of traditional power plants and photovoltaic plant [7, 10, 13].

Plant	Installed Capacity (MW)	Footprint (km^2)	2014 Energy production (TWh)	Calculated Capacity Factor (2014)	Calculation of PV power for the same area (MW)	Calculation of produced energy by the PV plant (TWh)
Itaipu	14,000	1,350	87,795	71.60%	214,615,384.615	330,180.40
Complexo Jorge Lacerda	857	2,000	4.7	62.70%	317,948,717.949	428,229.23
Eletronuclear	1,990	0,131	15.433	88.53%	0.209	0.0288

According to Table 1, the installed capacity for Itaipu is 14,000 MW, while Jorge Lacerda is 857 MW, whereas Eletronuclear is 1,990 MW. The energy production for 2014, according to the annual report of each plant were 87,795 TWh (Terawatt per hour) to Itaipu [7], 4.7 TWh to Jorge Lacerda [10], and 15.433 TWh to Eletronuclear [13].

The capacity factor for the three power plants was calculated in order to compare it with the percentage of the capacity factor of the photovoltaic systems. As shown in the literature, the capacity factor of a photovoltaic system varies from 15 to 18% [25]. As for the proposed study the amount used was 15% which is the typical minimum for the sizing of photovoltaic systems. In comparison with existing plants, the capacity factor calculated for Itaipu was 71.60%, 62.70% to Jorge Lacerda and 88.53% to Eletronuclear, using the produced energy data of 2014.

The low capacity factor of PV systems is explained by the intermittence of which these systems present, i.e., the solar source present interruptions in its supply [18]. This, added to the interferences that lower the productivity, such as soiling effects, partial shadding non-optimal tilt and azimuth angles and inverter performance [23], explain why PV plants have a lower capacity factor when compared to hydro, thermal and nuclear power plants.

According to the calculated results and shown in Table 1, it is noted that the installed photovoltaic power for three comparisons were significantly higher than the installed power of Itaipu, Jorge Lacerda and Eletronuclear. The Itaipu power plant would entail a photovoltaic plant of approximately 214,615,384.615 MW of installed capacity while Jorge Lacerda, using its entire area, would be able to accommodate an approximate PV installed capacity of 317,948,717.949 MW, whereas Eletronuclear present a capacity of 0.209 MW due its area being smaller than the first ones. The study show that the calculated values represent to Itaipu and Jorge Lacerda represent more than 15,000 to 370,000 times its installed capacity, respectively.

The projected annual photovoltaic generation for the respective areas also had significantly higher values, as using the area of the Itaipu reservoir, the annual projected PV energy is of approximately 330,180.40 TWh, while for Jorge Lacerda's area, is of approximately 428,229.23 TWh, whereas for the Eletronuclear'area, is of approximately 0.0288 TWh, which in that case, does not present technical viability. The comparison of environmental impacts for Itaipu, Jorge Lacerda, Eletronuclear power plants and projected photovoltaic plant is shown in Table 2, below.

Table 2. Comparison of the environmental impacts of each type of plant [26-29].

Environmental impacts comparative table	
Hydro Plant	Large flooded areas; impacts on geology and geomorphology of the site; silting, breaks and intensification of erosion process; impacts on flora and fauna; displacement of urban centers; impact on the local environment; emissions of greenhouse gases; gas emissions in the operation phase.
Thermal Plant	Emission of greenhouse gases and acid rain; hot water discharge on the environment, emission of sulfur and nitrogen dioxides, and particulate materials.
Nuclear Power Plant	Risks of reactor failure or accident, which might end up releasing radiation; accumulation of high-activity waste, for which there is no definitive solution. This waste is highly toxic and can last for thousands of years; contamination risks in the fuel cycle, generally caused by breaches in safety procedures.
Photovoltaic Plant	The production of the modules presents concerns about health and environmental security, and it is subject of study in the scientific community; the disposal of the modules represent environmental concern, as they may contain heavy metals.

The environmental impacts of the Itaipu hydroelectric plant are primarily related to the installation phase, because it demands large flooding areas, harming flora and fauna, displacement of urban areas, besides affecting the geology, geomorphology and hydrology. In the operating phase hydroelectric produce harmful gases, contributing to climate change due to the increase of greenhouse gases in the atmosphere [26]. As for the coal-fired power plants, they have lower impact on its phase, requiring smaller areas, however this plant is composed of several thermoelectric plants, forming a complex and thus a relatively larger area, which starts causing impacts on environmental degradation in coal producing regions, affecting soil, vegetation. Impacts occuring on water bodies are smaller than that of a hydroelectric, but thermoeletrics generates emissions of effluents and compromises the quality of water due to uptake for the cooling system, obstructing the waterway. The operation phase produces great impacts, especially the production of greenhouse gases and particulate materials on a large scale, damaging the air, the climate and negatively increasing atmospheric emissions [27]. Nuclear power plants, despite being considerably less harmful than fossil fueled thermal plants in its operating phase, and highly efficient considering energy production, presents other factors that might lead to environmental disasters, such as reactors accidents or failures and breaches on security procedures during the fuel cycle. Adding to this, there is the currently unavoidable problem of the high-activity waste disposal, which might harm the environment for a long period [28]. Photovolatic power plants do not present danger or environment impacts during its operation phase. On the other hand, there might be concerns regarding the components production, and its disposal, since those can contain heavy metals, as well the structure where they are mounted. The disposal itself can be very energy demanding, as mentioned earlier [29]. The analysis obtained regarding CO2 emissions to the photovoltaic generation in use and operation phase, when it presents zero emissions of these gases, but hydroelectric generation has an index of 5.98 g.CO_2 / kWh. The thermoelectric plants have a significantly higher rate, generating emissions in the order of 900 g.CO_2 / kWh. Nuclear plants have an average of 12 g. CO2 / kWh [30].

4. Conclusion

The results of this study show that photovoltaic plants with areas equivalent to Itaipu and Jorge Lacerda plants, even with significantly lower capacity factor, could still generate annual energy on the order of about 330,000 to 428,000 TWh. However, analyzing the Eletronuclear plants, a photovoltaic plant, with the same area, could not be viable when comparing its annual energy production, due to the higher capacity factor of the nuclear power plants. Regarding the environmental impacts, it is clear that the construction of a plant in the magnitude of Itaipu, besides the construction time, the whole area used will impact on the environment, due to the large environmental devastation, changes on the natural course of rivers, direct impacts on fauna and flora, and displacement of the people who live on site. There are studies that show that plants with reservoirs can emit greenhouse gases in its operation phase, due to flooded vegetation, located at the bottom of the reservoirs. On the other hand, thermal power plants, not only using large areas, they also present significant environmental and social impact due to the exorbitant greenhouse gases and CO_2 emissions. Moreover, those power plants are exploiting non-renewable natural resources, producing waste at the end of the process, which are very harmful to the ground and the effluents. Nuclear plants, despite not having a big CO2 emission, presents high risks regarding the toxic waste they produce, and the lack of a satisfying technology to deal with this waste properly is an important concern. That being said, the photovoltaic generation presents a good option of large power plants, although it has reduced impacts in its construction phase, due to the area that will be devastated. But in its operation phase, it presents advantages in relation to zero emissions of greenhouse gases and CO_2. By introducing this renewable source in the energy mix, many environmental impacts and pollutant emissions would be avoided.

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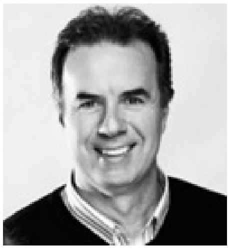

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