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Potentiality of Solar Photovoltaic Energy in Paraiba, Brazil, and the Relation with Sustainable Development

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Abstract

The use of non-renewable energy has been a major environmental concern and, therefore, there is a need to look for other renewable energy sources, especially photovoltaic's. In view of this, an attempt was made to quantify the potential of solar irradiance in the State of Paraiba, as an alternative source for conversion and use in electrical energy, these determinations being the main objectives. Global solar irradiance and solar photovoltaic data were extracted from scientific publications and/or made available on the websites of the National Institute of Meteorology (INMET), the Ministry of Mines and Energy and the National Electric Energy Agency, among others. For the case study, semi-structured questionnaires were applied in different business establishments in Campina Grande, with questions related to socioeconomic aspects and photovoltaic technology. Data were analyzed using descriptive statistics criteria and using an Excel spreadsheet. The main results indicated that the Brazilian energy matrix is predominantly from renewable sources. The Northeast is the second region with the highest production of photovoltaic solar energy and the State of Paraiba occupies its fourth position in the generation of this type of energy. The option of photovoltaic technology is a promising alternative, especially for rural areas, where there is not always a conventional electricity grid. The high availability of solar energy in northeastern Brazil, in almost all months of the year, especially in the state of Paraiba, demonstrates the existence of a high potential to generate electricity from photovoltaic systems. This technology contributes to local sustainable development, as it is an activity that generates employment and income, without degrading the environment.

Keywords

Solar Irradiance, Renewable Energy, Alternative Source of Energy Solar

1. Introduction

Among the permanent axes of debates on the agenda of the 21st century, global climate change becomes a central point in the debate, proposing profound and significant transformations in public policies, economic and social issues and, consequently, in human thought, that is, the need arises for a sharper look at sustainability (Giddens, 2010).

The term "sustainable development" became known through the Brundtland Report, when conceptualizing, for the first time, as being the development that satisfies present needs without compromising the capacity of future generations (CMMAD, 1991). In this way, a new vision of sustainable development involves socio-cultural and environmental aspects, thus reflecting on the quality of human life (Dias, 2011).

The Industrial Revolution in the 18th century promoted economic growth and wealth generation, while provoking an unbridled search for economic development propagated by the capitalist model of consumption, increasing population concentration in urban centers. This growth demanded a significant increase in the consumption of energy and natural resources, encouraging an unbridled search for goods and technologies designed to meet the basic needs of the population (Cunha & Augustin, 2014).

In this context, with an economic model of a predatory nature, there is a need to explore energy sources, especially those of fossil and non-renewable origin, which, in addition to causing negative impacts on the environment through the emission of greenhouse gases, cause concern because they tend to deplete their reserves (Granziera & Rei, 2015).

Thus, fossil and non-renewable energy sources, such as mineral coal, natural gas and oil, make the energy sector one of the main polluters of the environment through the emission of carbon dioxide (IPCC, 2014).

As a result, there is an urgent need to search for alternative sources of energy that do not degrade the environment, that have the least impact on species and their habitats, that offer safety and energy efficiency, consolidating themselves as a priority action today (Freitas & Dathein, 2013). This urgency is due to the short time that exists for the stabilization of greenhouse gas emissions at acceptable levels for the atmosphere (Giddens, 2010).

There are several ways to use solar energy: in lighting, in heating fluids and in the environment, thermal, among others. The process of converting solar energy into electricity takes place by capturing this energy through receiving materials, in which thermoelectric and photovoltaic effects occur (Kemerich et al., 2016).

The conversion process takes place silently, with no gases and no need for operators in the system. Photons are the only useful components for converting to the photovoltaic effect, in addition to having other applicability related to the thermal component, for heating liquids or generating electricity, through solar thermal panels (Lamberts et al., 2010).

The main industrial challenge is to produce accessories and complementary equipment for photovoltaic systems that focus on quality and lifetime, making them similar to modules based on crystalline silicon (Mariano & Urbanetz Jr., 2022).

Solar modules are usually installed on roofs and capture sunlight and convert it into electrical energy. However, photovoltaic systems are grouped into three types: connected to the grid (on grid), isolated (off grid) or hybrid, although they generate energy in a similar way (ABSOLAR, 2022).

The on grid system is connected to the public electricity distribution network and there is no device to store energy. The surplus produced returns to the conventional electricity grid, being accounted for in the so-called "energy credit" (Souza, 2020).

In the isolated system, since it is not connected to the electrical grid, all energy produced will be stored in batteries, in order to guarantee the energy supply at times without solar irradiance (Villalva & Gazoli, 2018).

In Brazil, it is essential to search for new alternative sources of energy that add quality and energy sufficiency, combined with low-cost technology and with less impact on the environment, that is, that establish a balance between exploration and environmental preservation (Stefanello, Marangoni, & Zeferino, 2018).

It is important to highlight that the global energy issue is one of the greatest challenges today and, therefore, alternative sources of energy that do not degrade the environment are sought (Almeida & Almeida, 2022).

The generation of photovoltaic energy is the technology that generated the most direct and indirect jobs when compared to other technologies (ABSOLAR, 2022). In the current international scenario, China is the country that stands out most in the generation of electricity from solar photovoltaic technology (IRENA, 2020).

The expansion of the participation of alternative sources of renewable energy in the energy matrix is an essential alternative to ensure energy quality and security. Brazil has a high energy potential, especially those of a renewable nature such as hydroelectric, wind, biomass and solar (Bandeira, 2012).

Among these alternative sources of renewable energy, solar energy is the source with the greatest growth prospects, even more so in Paraíba, which, due to its privileged location, at low latitudes (close to the equator), receives high rates of global solar irradiance in virtually every month of the year (Almeida, 2016).

Even in the face of these indicators, the State of Paraíba, as well as the Northeast region, is still at an incipient stage in terms of harnessing and using solar energy when compared to Germany, which receives about 40% less solar irradiance than the local least sunny in Brazil (Moreira Júnior & Souza, 2020).

Concerning public commitments, the global debate on environmental issues was preponderant for the inclusion of the environmental perspective in public policies in Brazil (Rodrigues et al., 2012). This discussion resulted, in 2015, in Brazil's commitment to the United Nations (UN) to intensify efforts to achieve, by the year 2030, the goals set out in the document that favors the seventeen "Sustainable Development Goals (Kunz et al., 2018; Susteras, 2021).

In this regard, every legal framework designed to protect the environment has the fundamental support of the 1988 Federal Constitution of Brazil, which guarantees, in its 6th chapter, the collective right to an ecologically balanced environment, essential for the life of society, simultaneously, in which it ensures the defense and preservation of the environment through the Public Power (Brazil, 1988).

In view of the legal support for regulating the insertion of renewable energies, Brazil has, among other laws, normative resolution 482 of 2012 of the National Electric Energy Agency (ANEEL, 2012), which establishes criteria for electricity generation by part of consumers and distributors, and Normative Resolution 687 of 2015, which expands and gives other possibilities for the power generation capacity of Normative Resolution 482 (ANEEL, 2015).

Bermann (2008) cites another important legal document to encourage the implementation of alternative sources; the incentive program for alternative sources of electricity (PROINFA) established by Law 10,438 of April 26, 2002 and revised by Law 10,762 of November 11, 2002. This program enabled a greater number of participating states and stimulated national industrial production, in addition to withdrawing low-income consumers from the division of the new energy system.

In the theoretical conception for a practical action, sustainability presupposes the search for a dynamic and necessary balance in the exploitation of useful resources for human activities, that is, A reflection on social practices, in a context marked by the permanent degradation of the environment and its environment ecosystem, creates a necessary articulation with the production of meanings about environmental education (Jacobi, 2003).

In the conceptual pursuit of sustainable development, Veiga (2008) points out that extremism that considers development an illusory process should be avoided; as if it were a belief, myth or even an ideological manipulation. Complementing this reasoning, Sachs (2002) emphasized the need to find an intermediate path "between ecological fundamentalism and arrogant economist".

Electricity is one of the manifestations inherent to the modern period and is understood in the context of social, political and economic transformations and access, the idea of freedom and development (Sachs, 2007; Guimarães et al., 2021).

In this context, an attempt was made to quantify the indicators of global solar irradiance in the State of Paraiba, as an alternative source for the conversion and insertion of photovoltaic solar energy in the electrical matrix, in the perspective of sustainable development, these determinations being the main objectives.

2. Materials and Methods

The work consisted of carrying out a diagnosis of the potential of solar and photovoltaic energy in the State of Paraiba, Brazil, and its relationship with sustainable development, using Exploratory, documental and applied research techniques, with a quantitative and qualitative approach.

The present work covers, mainly, the State of Paraiba, located in the eastern part of the northeast region of Brazil, with a territorial area of 56467.242 km^2, an estimated population of 4,059,905 million inhabitants, distributed in 223 municipalities and an index of human development (HDI) of 0.658 (IBGE, 2021).

The monthly and annual data of global solar irradiance of Paraíba were extracted directly from the National Institute of Meteorology (INMET) website, through the website: https://portal.inmet.gov.br, and the photovoltaics of Paraiba and other locations , on the websites of the Ministry of Mines and Energy (MME-https://www.gov.br/mme/pt-br), the National Electric Energy Agency (ANEEL-https://www.aneel.gov.br/), from the Electric Energy Statistical Yearbook (https://www.epe.gov.br/pt), from the Energy Research Company (EPE-https://www.epe.gov.br/pt), the Brazilian Association of Photovoltaic Solar Energy (ABSOLAR-http://www.absolar.org.br/), the Brazilian Atlas of Solar Energy (http://labren.ccst.inpe.br/) and other official documents.

In order to evaluate the main characteristics of the use of the potential to generate photovoltaic solar energy, thirty business establishments were chosen, in the city of Campina Grande, Paraiba, Brazil, from the three branches of activity (commerce, industry and service), where a questionnaire was randomly applied, structured and individual, with qualitative and quantitative questions referring to the socioeconomic profile and photovoltaic technology: What is the enterprise's field of activity? The size of the establishment? How long do you use the photovoltaic system? The purpose of using the photovoltaic system? The installed power, among others.

Calculations and analyzes of descriptive statistics, including the preparation of graphs and tables, were performed using the Excel spreadsheet.

3. Results and Discussion

The first living beings that inhabited Earth took advantage of sunlight to meet the simplest of needs, such as heating on cold days and drying on rainy days. Since that time, solar energy has been used for basic needs such as heating, drying grains and animal skins, among others.

In this context, photovoltaic technology stands out as the most efficient in converting global solar irradiance into electrical energy. However, the greatest scientific challenge is to evaluate the potential of photovoltaic energy generation, as it depends on temporal oscillations of global solar irradiance and/or insolation. These conditions agree with Zhu et al. (2019), when highlighting that the variability of the generation of this energy is intrinsically related to the availability of global solar irradiance and local meteorological conditions, above all, to cloudiness.

It should be noted, however, that the average hours of sunshine for the period:

1990 to 2020 varies from 2600 to 3200 hours of sunshine per year, with monthly averages in the hottest months (December) and the coldest (July), oscillating, respectively, between 260 and 280 and 220 and 240 hours of sunlight/month. These high insolation indicators, combined with those of global solar irradiance, prove the existence of a high potential to be explored for the generation of photovoltaic electricity.

The Paraiba is one of the Northeastern states with the highest indicators of global solar irradiance, which, according to the Brazilian Atlas of Solar Energy, has an annual average of 6.5 $KWh \cdot m^{-2}$ per day, surpassing the national average that varies between 4.5 and 6.3 $KWh \cdot m^{-2}$.

It is also reported that the average annual values of global solar irradiance, for the aforementioned State, exceed 2000 $KWh \cdot m^{-2}$, indicative potential for photovoltaic solar energy generation, which shows the importance of this technology not only to complement the conventional energy matrix, but to expand the use of this technology in the rural area of Paraiba, where there is not always electricity.

Comparing the averages of solar irradiance in the State of Paraiba, Brazil, with those of Germany (**Figure 1**), as it is a country that most converts this energy into photovoltaic's, it is verified that the annual averages oscillate between 949 and 1241 $KWh \cdot m^{-2}$ (average of around 1000 $KWh \cdot m^{-2}$), that is, half of what occurs in the State of Paraiba (2086.3 $KWh \cdot m^{-2}$).

Even if the Weather and Climate conditions in Germany are less favorable than those in Brazil, there is an efficient program of investment and insertion of photovoltaic technology, which gives it a capacity for use superior to that of Brazil.

This eastern European country is included in the list of the greatest economic and industrial powers in the world, which is why it seeks to insert a more sustainable energy matrix. Therefore, it has been investing in the implementation of renewable energies, in particular photovoltaic solar energy, with expressive results, although it occupies the 5th position, when compared to the 10 most producing countries (**Figure 2**), with China, in the lead.

In the environmental dimension, photovoltaic solar energy has the characteristic of being a clean energy source, that is, there is no emission of greenhouse gases in the process of electric generation. The development of photovoltaic technology influences the attraction of investments, heats up the market and generates jobs throughout the production chain, driving sustainable development.

Figure 3 presents the global temporal evolution in the generation of jobs related to wind, hydroelectric and photovoltaic energy sources.

It can be seen (**Figure 3**) that photovoltaic technology was the only one to present continuous evolution in the generation of jobs, in the ten years analyzed, when compared to wind and hydroelectric, growing at an average annual rate of 21.54%, while wind grew 8.2%.

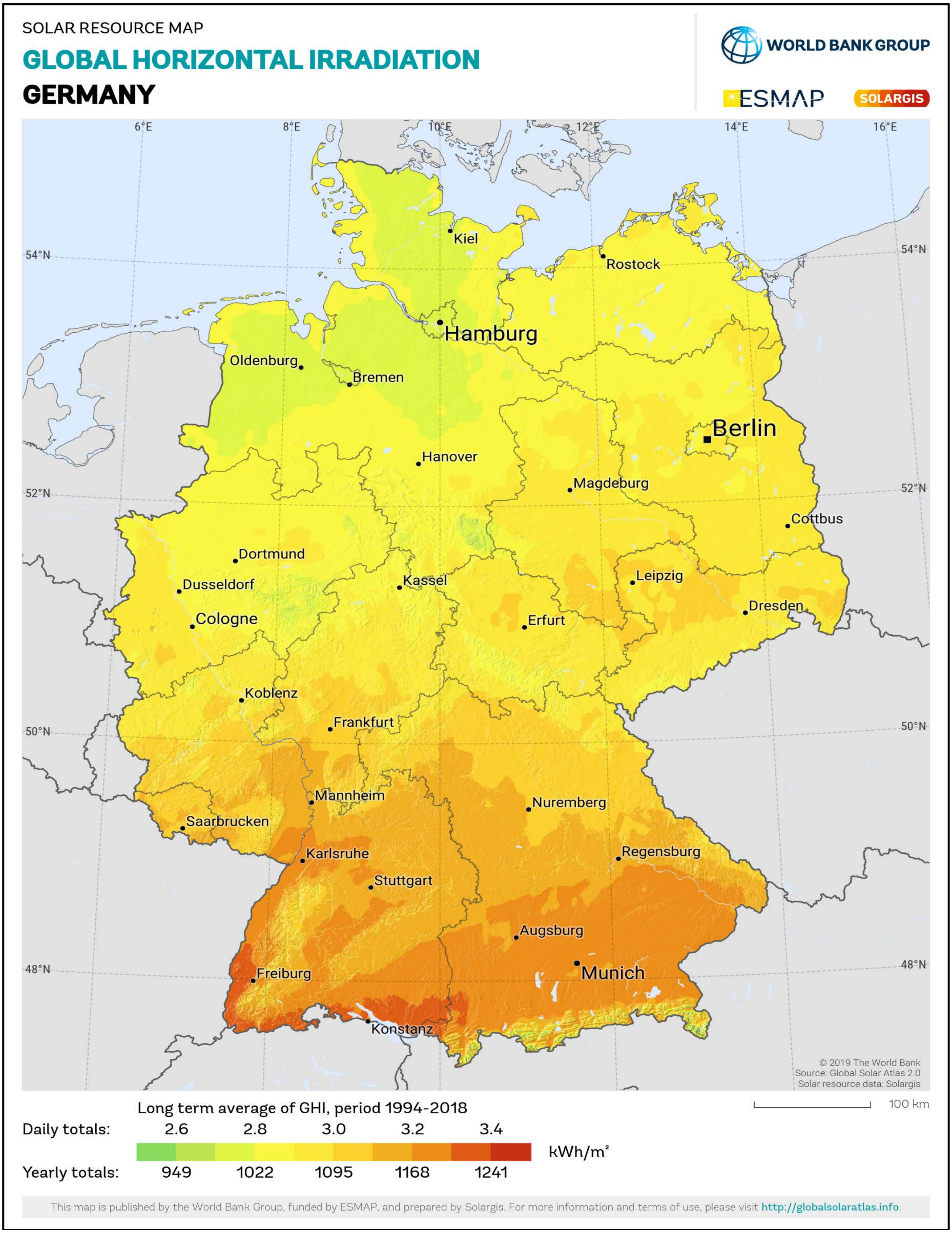

Figure 1. Sketch with annual averages of solar irradiance in Germany. Fonte: Adapted from Global Solar Atlas, 2022. Available at: https://globalsolaratlas.info/detail.

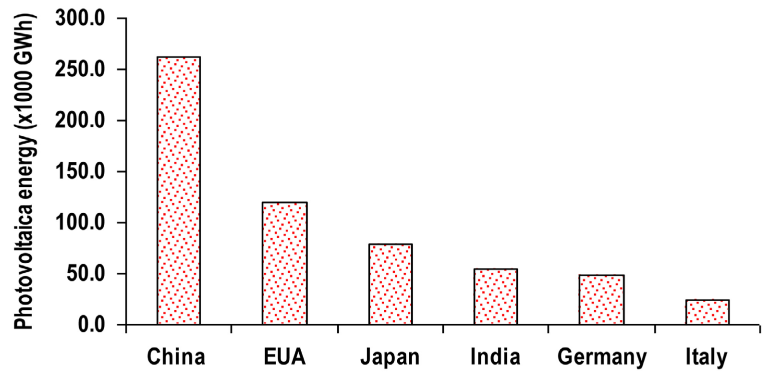

Figure 2. Indicators of photovoltaic solar energy generation, in 2020, of the six largest countries. Source: Data from IRENA, 2022. Prepared by the author. Available from: https://www.irena.org/Statistics/View-Data-by-Topic/.

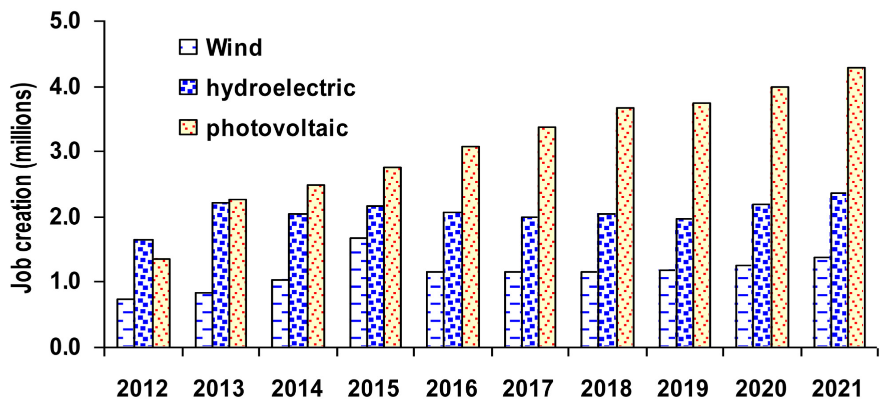

Figure 3. Temporal evolution (worldwide) in the generation of employment by renewable energy sources. Source; Da Adapted from IRENA, 2022. Available at: https://www.irena.org/Statistics/View-Data-by-Topic/Benefits/Employment-Time-Series.

It is noteworthy, however, that said energy source has an economic advantage, due to the reduction of about 95% of the value of the energy bill, to be paid by the consumer to the concessionaire, in addition to being an imperative to mitigate possible effects of climate change, which corroborates the reports by Giddens (2010).

In this context, photovoltaic solar plants may have some disadvantages, a priori, due to environmental degradation, as reported by Scherer et al. (2015), for autonomous systems (off grid), because there is a need for batteries to store energy, which is not generated during periods of intermittent solar irradiance (day/night), including cloudy days.

The energy matrix of the Northeast is currently made up of more than 1361 projects generating almost 50 GW of granted power, of which 80% are from renewable sources (**Figure 4**), with emphasis on wind power, with 42% of the total.

These frequencies demonstrate that the energy matrix of the Northeast has a similar profile to the national one, with a predominance of energy sources of a renewable nature. This trend is confirmed by ANEEL (2022), in which the

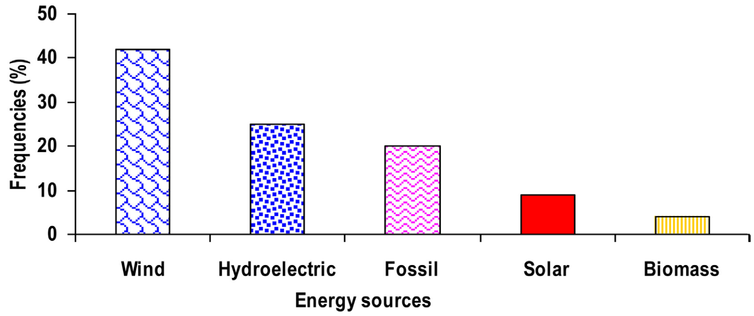

Figure 4. Relative frequency (%) of renewable energy sources in Northeast Brazil. Source: ANEEL data, 2022, prepared by the author (2023).

Northeast emerges as the second region that most produces electricity in the national system, with about 26% of participation in the national matrix.

The centralized production of electric energy in the Northeast, from photovoltaic solar source, generated in the plants (parks), which granted potential, exceeds 4.5 GW, equivalent to 9.0% of the generation in the regional energy matrix, with uneven participation by State as shown in **Figure 5**.

The nomenclatures described as granted and supervised powers corroborate the descriptions made by Araújo et al. (2022), the granted power is authorized by ANEEL and the inspected power is the one produced in the generating unit.

As can be seen (**Figure 5**), Bahia is the northeastern state with the highest power granted (1356 MW) followed by Piauí (1249 MW), Ceará (702 MW) and Paraíba (461 MW). The states of Alagoas, Maranhão and Sergipe still have very small powers granted, on the order of 7 mega watts.

The numbers of the northeastern states may be a reflection of the lack of government incentives, narrow legal protection, a low diffusion of the viability of photovoltaic technology combined with a high acquisition cost. These factors influence and converge to the lowest percentages, when compared to the states in the Southeast of Brazil.

All photovoltaic solar energy generation, from the on grid system, is interconnected to the conventional transmission grid and is growing rapidly in Brazil. In 2021, the country was the 4th in growth in the world, with an increase of 5.7 GW, with thousands of power plants and/or panels installed on the roofs of homes, industries, public and private organizations. This generated electrical energy is injected into the national electrical system.

One of the great challenges of the Brazilian and world productive sector is the combination of sustainable policies with increased competitiveness. The use of photovoltaic solar energy to generate electricity and solar thermal energy to heat water is currently the technology that best translates this trend.

Brazil surpassed the mark of 20 gigawatt of installed power, equivalent to almost two Itaipu plants and 9.6% of the national electricity matrix. Despite the impact on the national economy, due to Covid-19, the Brazilian photovoltaic market generated, in 2020, more than 86 thousand new jobs throughout the territory (ABSOLAR, 2022).

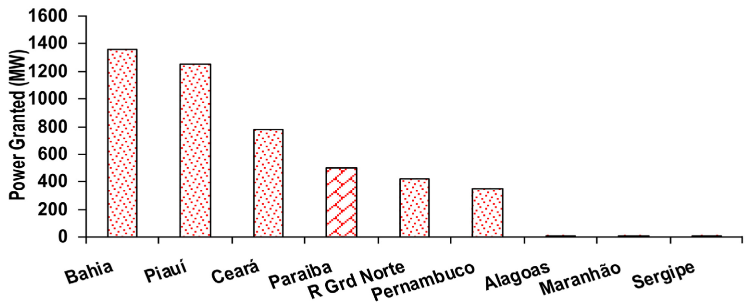

Figure 5. Comparison of the granted potential of the centralized generation of photovoltaic energy by Northeastern States, Brazil. Source: ANEEL data, 2022, prepared by the author (2023).

The evolution of photovoltaic solar energy in the state of Paraiba is characterized by the use of distributed energy, with the first plants installed in 2018. The Angico I and Malta photovoltaic parks, which make up the Angico/Malta complex (**Figure 6**) and the Coremas II venture, which make up the current Coremas solar complex (**Figure 7**), operated with 81.4 MW of granted power.

In 2019, the Coremas I plant came into operation, with a production of over 27 thousand KW and, in 2020 and 135 MW, in 2021, which corresponded to 100% of its granted powers (ANEEL, 2022).

It is reported that in this initial period of installation, with investment from national and international companies, approximately R$ 1.1 billion reais were invested in the aforementioned plants and generated more than 1650 jobs.

The use of distributed photovoltaic generation, in business establishments in the city of Campina Grande, Paraiba, Brazil, in the three branches of activity: commerce, industry and service, were diagnosed by applying a structured questionnaire, with questions related to: consumption, economic profile, type of generation of installed systems, economy, the main motivation for acquiring this technology, among others.

The Unifacisa University Center, located in the Itararé neighborhood, in Campina Grande, Brazil, has an on-grid photovoltaic solar system, interconnected to the energy distribution network, with an installed power of 1500 KWh, which meets the institution's electricity demand.

This system was installed on Unifacisa's university main building, including the parking areas (**Figure 8**).

Regarding the business size (**Figure 9**), it is observed that 70.0% of the establishments in Campina Grande are Microenterprises, whose annual billing limit is around R$ 360 thousand. 16.7% are small businesses (ETP) with annual revenues ranging from R$ 360,000 to R$ 4.8 million, and 10% of establishments are classified as Large Companies, with annual revenues greater than R$ 300 million.

With regard to the level of education of the owners of establishments, 44.3% of respondents have completed higher education. The main characteristics related to photovoltaic systems, about 80% were installed in the last three years, 96.7% of them are used to generate electricity, 60.0% opted for individual generation and 90% of establishments have installed power above of 75 KW, with predominance

Figure 6. Aerial view of the Angico and Malta photovoltaic complex, Paraiba, Brazil.

Figure 7. Aerial view of the photovoltaic solar complex in Coremas, Paraiba, Brazil.

Figure 8. Aerial view of the on-grid photovoltaic solar panel, installed in the parking areas of the University Center of Unifacisa, in Campina Grande, Paraiba, Brazil.

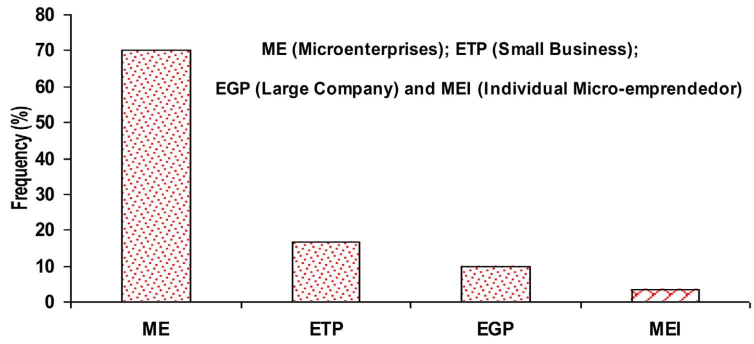

Figure 9. Relative frequency (Fr, %) of use of the photovoltaic system according to business size. Source: elaborated by the author (2023).

of mini-generation according to ANEEL RN 687/2015 (ANEEL, 2015).

Noteworthy, however, is the savings in the monthly energy bill; 63.3% of establishments saved more than 70% when compared to Energisa's conventional system. Even considering that the costs of implementing photovoltaic technology are still high, the return on the application compensates the investment, which is explained by more than 90.0% of the owners of the establishments, as satisfied or very satisfied.

In this context, when asked about the degree of importance of photovoltaic energy, 83.3% answered that solar energy is very important, that is, they have a positive view of this technology, both in relation to the environment and economy.

Some advantages and motivation for acquiring the photovoltaic system are, mainly, those of preserving the environment, reducing operating costs and property valuation, a technology that result in increased profits and other socio-environmental benefits.

4. Conclusion

Fossil and non-renewable sources, in particular those derived from oil and mineral coal, are still the most used in the generation of electricity worldwide, although they are highly polluting and harmful to the environment.

Brazil has a predominant energy matrix of renewable sources, equivalent to more than 80%, against about 30% of the rest of the world.

The Brazilian Northeast is the second region with the highest production of photovoltaic solar energy and the State of Paraiba occupies the fourth regional position.

The largest percentage of electricity in Brazil comes from hydroelectricity. Despite being a clean and renewable source, it is a source that depends on rainfall patterns.

The high potential of solar irradiance in the State of Paraiba, qualifies it as a priority geographic area for investment in the conversion of solar energy into photovoltaic's, in addition to generating employment and income.

Regarding the size of the business sector, in establishments in Campina Grande, Paraiba, Brazil, photovoltaic technology predominates in micro and small companies. In addition, more than 80.0% have a positive view of this technology, both in terms of the environment and the economy.

The option for photovoltaic technology is a promising alternative, especially for rural areas, where there is no conventional electricity grid, for residential purposes and for agricultural activities by small family producers.

Photovoltaic systems in the State of Paraiba have the potential to expand and contribute to sustainable development, as they contribute to the generation of employment and income, based on centralized and decentralized generation that does not directly depend on the electricity supplied by the electricity concessionaire.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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