Prospecting of the Solar Energy Potential in the State of Goiás - Brazil

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Abstract. As urbanization progresses, the UN-Habitat projection indicates an increase in urban population from 56% to 68% by 2050. With urban growth, there is a corresponding rise in energy consumption and CO^2 emissions, necessitating decisive actions to mitigate climate change. Promoting sustainable cities through specific policies is vital to address these challenges. Sustainable development, recognized as one of the 17 global goals set by the United Nations to be achieved by 2030, plays a crucial role in this context. This study aims to assess the energy potential, determine the most suitable areas for installing solar energy in electricity conversion systems, and analyze the history of electricity generation and consumption in municipalities with open data from regulatory agencies. This goal aligns with the global effort to transition to cleaner and renewable energy sources, contributing to sustainable infrastructure development.

Keywords. Solar Photovoltaic Energy, Sustainable Development, Prospecting.

1. Introduction

The vital presence of energy from the Sun is imperative for life on Earth. Not only would the integrity of the food chain be compromised, but the Earth's temperature would be so reduced that it would make life as we know it unviable [1].

Humanity's survival, well-being, and progress are substantially linked to the human ability to generate, control, and distribute energy. Electricity plays a crucial role in economic and social development and in promoting the population's quality of life. Therefore, adopting responsible practices not only results in reduced consumption and expenses for consumers but also decreases the need for expansion of the energy system.

In practice, sustainability requires that society adopt new habits and develop a development model that promotes care for ecological balances, operating within the limits imposed by nature.

It is essential to highlight that pursuing sustainability does not imply a return to the past but rather a new approach to the shared future. The core of this concept does not lie simply in avoiding consumption but in consuming responsibly, adopting practices that respect environmental limits, and promoting the preservation of resources for future generations [2].

2. Renewable Energy

2.1 Solar Energy

The photovoltaic effect was identified by the French physicist Edmond Becquerel in 1839. Notably, Edmond Becquerel, the father of Henri Becquerel, renowned for his contributions to the studies of radioactivity, used an electrochemical cell to generate a potential difference between two electrodes when the device was exposed to light [3].

Solar radiation stands out as one of the most significant renewable energy sources, especially in the spectral region of infrared and visible light. This energy can be directly converted into heat or electricity through appropriate materials and devices. A photovoltaic cell is an example of a device capable of directly converting light into electrical energy, generating a voltage and electric current under illumination.

2.2 Brazil's Solar Energy Potential

Geographic location is a crucial element impacting Brazil's photovoltaic energy generation. The most suitable areas for this production are those characterized by high solar irradiation, notably in the Northeast and some specific areas of the Midwest and Southeast regions.

The Northeast region displays the highest values of global solar irradiation, with the highest average and the lowest annual variability among all geographical regions. The country's maximum solar irradiation values are observed in the central region of Bahia (6.5 kWh/m^2/day), including, partially, the northwest of Minas Gerais. Throughout the year, climatic conditions provide a stable regime of low cloudiness and high incidence of solar irradiation for this semi-arid region [4].

2.3 Generation Capacity and Growth of Distributed Generation in Brazil

In Brazil, the forecast by the National Electric System Operator - ONS indicates a 20% increase in the load of the National Interconnected System - SIN by 2026, compared to the peak in 2020, with regional variations of 26% in the Northeast and 17% in the Southeast and Midwest. In 2022, the installed capacity of the SIN was 178,555 MW, distributed among hydroelectric plants (109,127 MW), thermoelectric and nuclear plants (24,886 MW), and wind and photovoltaic sources (28,713 MW) [5].

Projects for 2026 estimate a growth of 200,255 MW, highlighting an increase of 114% in solar plants (13,511 MW) and 32.5% in wind farms (29,670 MW). This growth of renewable sources reflects the effort of public and global policies to decarbonize the energy matrix. Signaling a more sustainable energy future for Brazil [5].

2.4 Electricity Consumption in Brazil and the Role of Cities

Energy use in contemporary society predominantly occurs in urban settings, where 64% of consumption and approximately 70% of greenhouse gas - GHG emissions are concentrated [14]. Considering that more than half of the world's population resides in urban areas, this concentration provides a conducive environment for collaboration among various social agents to find solutions that allow for more efficient and organized coexistence.

Among the opportunities offered by urban centers is access to improved education, resources, and services superior to those available in rural areas, even considering the recent expansion of communication networks and digital media to smaller localities [6]. Energy plays a fundamental role in this context, with various forms of use in daily urban life for different purposes. However, the challenges associated with its adaptation have been evident over time, whether due to supply shortages (in terms of availability) or the constant growth of demand in urban areas.

Various energy conservation practices have been implemented to address this issue, including measures and energy efficiency programs that gained prominence from the 1970s, especially during oil crises. Subsequently, new approaches, such as implementing processes based on the circular economy, have contributed to optimizing energy use.

Efficient energy management is crucial for cities to play a fundamental role in society's energy transition process. Ascimer outlines the main objectives of a smart city as the pursuit of efficiency in urban services, improvement of the population's quality of life, and sustainable urban development. These objectives reflect the continuous development of individuals in the urban environment. Energy use must accompany and, in some cases, anticipate this process to enable its success.

From the energy consumption perspective, discussions about smart cities must incorporate considerations relevant to the energy transition context, such as climate change and the Sustainable Development Goals- SDGs [7].

The coordination of this process by local governments requires a transformation in governance, seeking the application of technology to expand political participation, services to citizens, and administrative efficiency, conceptualized by Giffinger et al. [8] as "Smart Governance" – one of the six characteristics of a smart city, as highlighted in the first technical report of this series [9].

The challenge of transitioning the energy system to a low-carbon economy incorporates various aspects closely related to the urban environment. Circular economy, energy efficiency in buildings, the use of distributed energy resources - DERs, and the adaptation of urban mobility emerge as some of the main strategies to promote intelligence in using energy in cities. In a "smart city" the incorporation of technology aims to make urban centers more sustainable, contributing to improving the quality of life of their population.

3. Study Area

The state of Goiás, located in the Central-West region of Brazil, was selected as the scenario for this study due to its distinct geographical and demographic characteristics. Covering an area of 340,242 km², Goiás is the seventh-largest Brazilian state in territorial extension, standing out for its strategic geographical position. It borders Tocantins to the north, Minas Gerais and Mato Grosso do Sul to the south, Bahia and Minas Gerais to the east, and Mato Grosso to the west, granting it diversified access to different regions of the country [10].

Figure 1 - Map of Brazil highlighting the location of Goiás

With over 7 million inhabitants distributed across 246 municipalities, according to data from the Brazilian Institute of Geography and Statistics – IBGE in 2022, Goiás presents a rich social and economic mosaic. This diversity and its geographical location make Goiás a suitable place for researching the development and implementation of photovoltaic solar energy technologies. The choice of Goiás as the study object is relevant for understanding this specific state's solar energy generation potential. It serves as a model for assessing the viability and impacts of such investments in other regions of Brazil with similar characteristics. This focus on the state of Goiás aims to significantly contribute to advancing the Brazilian energy matrix, promoting sustainability and energy efficiency in a regional and national context [10].

3.Results and Discussions

3.1 Solar Power Plants in Goiás

The methodology employed for mapping the solar power plants in the state of Goiás involved using open data provided by the National Electric Energy Agency - ANEEL, aimed explicitly at micro and mini-generators of distributed energy in the state. This procedure was guided by Normative Resolution No. 482/2012, allowing a detailed analysis of the distributed solar energy generation ventures in Goiás. Table 01, derived from this research, presents a set of crucial data for understanding the solar energy scenario in the state, categorizing the ventures according to various significant variables for their identification and operation.

The mentioned variables include the connected distributor, project code, numerical core of this code, holder's name, production class, subgroup, number of consumer units benefiting from the generated credits, system connection date, type of production unit, energy source, installed power, municipality, and federative unit where the venture is located. These pieces of information are crucial for a comprehensive analysis of the photovoltaic solar energy infrastructure in Goiás, offering a solid foundation for evaluating the energy potential and the efficiency of solar installations in the state.

The unit of measurement used to express the installed power is the kilowatt (kW). At the same time, the amount of energy produced or consumed is recorded in kilowatt-hours (kWh) or megawatt-hours (MWh), as per the standard adopted by the National Electric Energy Agency - ANEEL. These data are essential for quantifying the productive capacity of the micro and mini-distributed generators, allowing an accurate assessment of the impact of these installations on the energy matrix of Goiás. The analysis of these data is crucial to understanding the distribution and effectiveness of solar energy systems in the state and identifying potential areas for future investments and expansion of distributed solar energy generation.

The analysis of data provided by the open data site of the National Electric Energy Agency - ANEEL reveals a substantial growth in the last decade in the adoption of distributed generation systems, especially regarding photovoltaic solar energy. The selection and analysis of these data, based on the generation date of the plants, provided a detailed view of the annual evolution of the installed capacity and the number of plants in operation from 2018 to 2022, as detailed in Table 1.

The methodology adopted for screening and analyzing the data involved segmenting the distributed generation plants according to the year of their connection to the network, allowing a chronological assessment of the development of Brazil's photovoltaic solar energy sector. This historical approach is essential to understanding growth trends, adoption patterns, and the expansion of distributed generation capacity in the country, especially in the context of the state of Goiás, which serves as the focus of the present study.

The annual data analysis on distributed generation plants, especially in the context of photovoltaic solar energy, reveals profound implications for the impact of energy policies, technological advancements, financial incentives, and the growing awareness regarding sustainability and the importance of renewable energies. This chronological evaluation allows us to identify how political and regulatory decisions have shaped the solar energy market, directly influencing the pace and scale of adoption of this technology.

Energy policies, such as ANEEL's Normative Resolution 482/2012 (which established conditions for distributed generation in Brazil), have stimulated the sector's development. Creating a favorable regulatory environment is crucial to ensuring the security and attractiveness of investments in solar energy, directly reflecting the annual increase in registered photovoltaic installations.

Technological advancements in solar cell efficiency and reducing production and installation costs also play a vital role. These advancements not only make solar energy more accessible to a broader range of consumers and investors but also increase solar energy's competitiveness relative to other energy sources, boosting its large-scale adoption.

Financial incentives, such as specific credit lines, subsidies, and tax exemptions, are effective instruments for promoting the expansion of solar energy. They lower financial barriers to entry, making solar energy investment more attractive to households, businesses, and large-scale energy producers.

Finally, the growing awareness of sustainability issues and the urgency to combat climate change have driven the demand for renewable energies. Solar energy, one of the cleanest and most abundant forms of renewable energy, is at the forefront of this energy transition. Society is increasingly aware of the environmental, economic, and social benefits of solar energy, reflected in the growing adoption of this technology.

Therefore, the analysis highlights the impressive growth of the photovoltaic solar energy sector and provides a comprehensive understanding of the factors contributing to this growth. This analysis is essential for guiding future policies, encouraging continuous innovation, developing more effective financing strategies, and fostering a culture of sustainability, thus ensuring steady progress towards a renewable energy future.

By detailing the year-on-year growth, Table 1 demonstrates the upward trajectory of distributed generation, underlining Brazil's commitment to the energy transition and the crucial role of solar energy in achieving a cleaner, more efficient, and sustainable energy future. This survey is an indispensable tool for managers, investors, and policymakers in making informed decisions, aiming to maximize photovoltaic solar energy's environmental, economic, and social benefits.

Table 1 - Solar Power Plants in the State of Goiás from 2018 to 2022.

Date of conection	Average area	Average Power	Average Number of Modules	Number of Power Plants
2018	98,7	13,5	47,5	1084
2019	120,2	14,5	49,7	4580
2020	71,7	16,9	58,8	8909
2021	77,2	11,5	34,5	16609
2022	77,2	9,8	25	11749

The data indicate a notable increase of 24% in the installation of photovoltaic power plants in the state of Goiás from 2018 to 2022. This growth reflects the positive impact of strategic planning and implementation in the renewable energy sector within the region.

Furthermore, the observed expansion underscores the lasting influence of incentive policies for photovoltaic installations. These policies, which have been carefully researched and applied in previous years, demonstrate their effectiveness and capacity to drive substantial progress in sustainable energy development over an extended period.

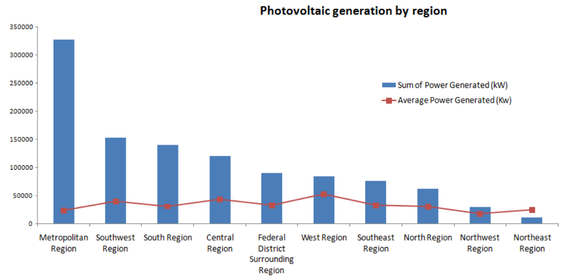

Figure 2 – Photovoltaic generation by region

When examining the distribution of photovoltaic generation across different regions within the state of Goiás, it becomes evident that the state's metropolitan area stands out as the leading contributor to overall production. This observation highlights the metropolitan region's pivotal role in harnessing solar energy for electricity generation within the state.

Furthermore, the analysis reveals that the average generation, inherently linked to each site's solar irradiation levels, does not directly correlate with the total generated power. This insight suggests that factors beyond mere solar exposure, such as technological efficiency and system capacity, play crucial roles in the effectiveness of photovoltaic energy production.

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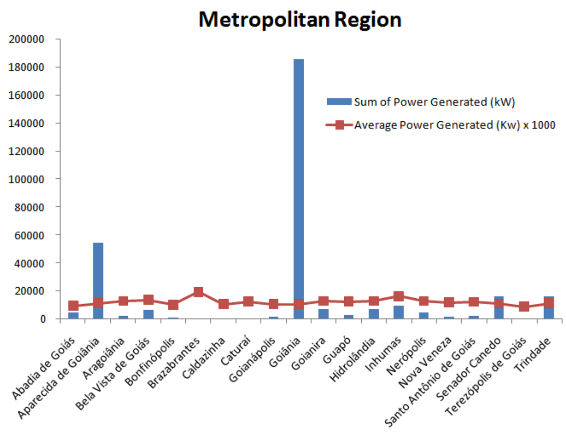

Figure 3 - Photovoltaic generation in Metropolitan Region

3.2 Potential for Photovoltaic Power Plant Installation in Goiás

Figure 4 is a map that highlights the significant potential for installation in the state of Goiás, which, according to the range of installation potential, evaluated together with the area and territorial representativeness of the state, has only 6.2% (equivalent to 22,064 km^2) of the territory unsuitable for the installation of these plants, leaving 93.8% of the area for this purpose. Additionally, 92.5% of the state has installation potential above 60%. Another positive datum is that the majority of its area (182,868.1 km^2) presents a potential of 80% to 90%, representing 51.2% of the territory, and a considerable part of the state (31%) has a potential of 90% to 80% [13].

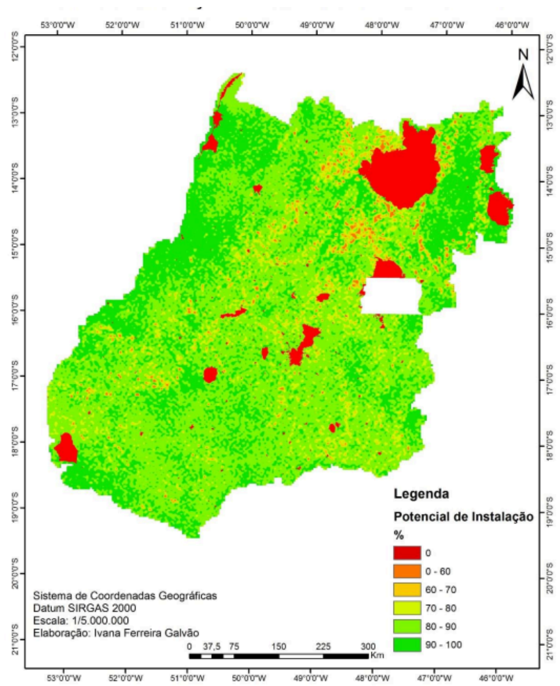

Figure 4 - Potential for Photovoltaic Power Plant Installation in Goiás

According to the map, it is possible to ascertain that, given the approach of this study, the most prominent areas with optimal potential, ranging from 90% to 100%, are located in the extreme northeast of the state, as well as the northwest and west. It is also possible to analyze that the state, in general, presents a high installation potential. Moreover, even considering all conservation units as inappropriate for this activity, 93.8% of the territory has potential.

4. Conclusion

The increase in renewable energy generation benefits the planet, such as reducing carbon dioxide and methane production. However, it also has positive socioeconomic impacts on the cities involved, including job and income generation, growth of the local economy, increase in tax collection, enhancement of learning in this technology, and improvement in the security, reliability, and supply of electric power.

Although initially more expensive, renewable energy sources expand through government incentives for production, thus, with gains in scale and technological advancements, the result is an increase in production, a decline in costs, and ultimately, competitiveness in the energy market [11].

Incentive programs are essential for reducing technology costs and promoting economic viability. For example, incentive programs for the use of photovoltaic panels on rooftops, launched in the 1990s and practiced in Germany, Japan, and other countries, significantly increased decentralized generation within a few years [12].

It is emphasized that solar photovoltaic energy generation can be centralized, with larger plants, or decentralized, known as distributed generation, located in houses, commercial and public buildings, condominiums, and rural areas. Different incentive policies are adopted for each, aligning with the context and power generated [11].

Moreover, this study shows that Brazil, specifically the state of Goiás, has immense potential for solar photovoltaic generation. It could greatly help to augment the Brazilian energy matrix and move away from using fossil fuels that harm the planet so much. Adopting correct and well-applied public policies makes it possible to improve the Brazilian energy matrix and encourage economic policies, job creation, and the improvement of the population's quality of life.

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