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Development of a software tool for photovoltaic system sizing: Enhancing precision and efficiency in renewable energy projects

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Abstract
The increasing demand for renewable energy highlights the importance of tools that enhance the efficiency and accessibility of photovoltaic systems. This study presents the development of a software tool for sizing photovoltaic solar systems, designed to streamline processes and improve project performance. Built on the Django framework, the application integrates solar irradiation data, equipment specifications, and user inputs to deliver accurate simulations and optimal system configurations. The tool was validated using real-world data from the Brazilian Solarimetric Atlas, demonstrating its precision and usability in diverse scenarios. By addressing challenges such as under dimensioned and over dimensioned projects, the tool supports the transition to sustainable energy practices while offering economic benefits for users. This research contributes to the adoption of distributed solar energy generation and reinforces the role of technology in mitigating environmental impacts and promoting clean energy solutions.

Keywords: Photovoltaic systems; solar energy, software development, renewable energy optimization

1. Introduction

Human actions are undoubtedly impacting Earth, as seen in climate change caused by excessive greenhouse gas (GHG) emissions resulting from the combustion of fossil fuels used in electricity production. Additionally, the potential depletion of natural resources, such as coal and oil, has been a concern for researchers and scientists since the 1990s. Thus, efficient resource use and the pursuit of sustainable development are essential demands of the 21st century [1].

The Sun is an inexhaustible source of energy, vital for life on Earth. Its radiation can be harnessed in various ways, such as in the production of thermal and electrical energy. One example is photovoltaic solar energy, which involves the direct conversion of light into electricity using photovoltaic cells, semiconductor devices responsible for this process [2].

According to Sebrae [3], the demand for renewable energy sources, especially photovoltaic solar energy, has been growing significantly in Brazil and globally. In addition to the pursuit of clean and sustainable energy, the goal is to mitigate the continuous tariff increases imposed by energy concessionaires, reducing costs for families and businesses.

Currently, in Brazil, it is possible to generate one's own energy and inject the surplus into the concessionaire's grid. Regulated by ANEEL Normative Resolution No. 1,000/2021, energy generated and not consumed is fed into the grid, generating credits to offset future bills, valid for 60 months, or used in other registered units within the same concession area, under the modalities of remote self-consumption, shared generation, or condominiums [4].

According to Carvalho [5] from Instituto Solar, proper photovoltaic system sizing is crucial to ensure optimal performance and cost savings. This requires analyzing average monthly consumption, regional solar irradiation levels, and equipment efficiency. Subsequently, the total system power must be calculated, and the inverter defined.

According to Adekanbi *et al.* [6], the growing global energy demand and environmental impacts of fossil fuel usage underscore the need for clean energy sources like solar. Despite its advantages, photovoltaic system efficiency is affected by environmental factors, such as dust accumulation on panel surfaces. The authors noted that particle buildup could reduce efficiency by up to 40% in desert areas, depending on dust deposition rates and cleaning frequency. Advanced technologies, such as electrodynamic screens, have been identified as promising solutions to mitigate these losses, although high costs pose a challenge for large-scale adoption. Additionally, factors such as panel tilt angles and rainfall frequency significantly mitigate 'soiling' effects.

In Brazil, photovoltaic solar energy plays a vital role in transitioning to a more decentralized and sustainable energy model [7]. Researchers emphasize the evolution of distributed generation in the country, highlighting opportunities provided by solar energy to diversify the energy matrix and mitigate environmental impacts. Moreover, they underline the importance of balanced regulatory frameworks to foster sector growth while aligning the interests of all stakeholders.

Regulatory changes in Brazil, such as Law 14,300, redefined the economic parameters for distributed photovoltaic solar energy generation [8], impacting its viability and expansion. Researchers analyzed solar generation conditions in different regions of Mato Grosso do Sul, using fuzzy logic to assess solar energy's attractiveness in varied scenarios. Results indicated a positive correlation between productivity and tariff increases with project attractiveness, although new regulations extended average investment return times (payback). Nonetheless, specific conditions, such as reduced installation costs, were identified as mitigating factors. According to the authors, distributed generation offers significant opportunities, particularly in agriculture, contributing to regional economic and energy sustainability despite regulatory changes.

In Central Asian countries, where many consumers experience frequent disconnections from the power grid, solar energy emerges as a viable solution for promoting sustainable electrification [9]. In this context, researchers investigated methodologies for calculating the capacity and efficiency of autonomous photovoltaic systems, emphasizing their relevance in regions with limited access to conventional electricity. The study analyzed module nominal power, connection configurations, battery storage capacity, and inverter sizing, using statistical methods to project energy demand. Results indicated that autonomous systems could meet consumer needs with a daily demand of up to 4 kWh, highlighting their potential as a sustainable solution to reduce electrification deficits and foster socioeconomic development in remote areas.

For Silva and Filho [10], access to accurate tools and data, such as those provided by the Brazilian Solar Energy Atlas, is critical for planning and installing photovoltaic systems. This study presents the development of a web tool to calculate solar radiation on inclined planes, enhancing precision in solar project sizing in Brazil.

According to Abdoos *et al*. [11], advanced machine learning techniques, such as convolutional neural networks, have the potential to improve solar energy generation forecasts in Mediterranean regions. The study highlights how technological advancements, government support, and reduced installation costs drive solar energy expansion, promoting energy sustainability and reducing carbon emissions.

This work presents the development of software for sizing photovoltaic solar systems, aiming to streamline the process and ensure optimal system performance. The tool facilitates customer conversion through quick responses, continuous process improvement, and avoidance of issues such as undersized or oversized projects.

2. Materials and methods

2.1 Research Design

This study adopted an applied approach, focusing on the development of a technological tool for sizing photovoltaic systems. The goal was to create an efficient software tool, based on the Django framework, to meet the needs of solar energy professionals by offering greater calculation precision and agility in the simulation and sizing process.

The research was structured into three main phases:

- **Planning:** In this phase, system requirements were defined based on a detailed analysis of user needs and gaps identified in the literature. The planning included specifying functionalities and gathering the necessary data for calculations.
- **Development:** The tool was developed using Django as the main framework, due to its robustness and flexibility for web applications. Modules were implemented for calculating solar irradiation, equipment sizing, and presenting results through graphical interfaces.
- **Validation:** The system was tested through simulations across different scenarios using real data from the Brazilian Solarimetric Atlas [1]. Images generated during the simulations were included in the study, demonstrating the tool's functionality and precision.

2.2. Tool Implementation

Technologies Used

The application was developed in Python, using Django for the backend and HTML/CSS and JavaScript for the frontend. Libraries such as Math were employed for simulation calculations.

Database

Meteorological and panel efficiency data were stored in an SQLite database during development, with the option to migrate to PostgreSQL for production.

Calculations and Algorithms

The tool uses data [1] with monthly averages calculated using the Perez transposition model to determine solar irradiation on inclined planes. The sizing algorithm considers variables such as average monthly consumption, regional irradiation, losses, and equipment efficiency.

The Eq. (1) presents the calculation of the daily average energy generated (E_d) by a photovoltaic system, based on the daily average solar irradiance for an inclined surface. This calculation is essential for determining the feasibility and efficiency of the system in different regions. It takes into account specific parameters, such as the local average irradiance level (I) and the characteristics of the equipment used, including the module area (A_m) and module efficiency (η_m), providing a solid foundation for accurately sizing the photovoltaic system.

$$E_d = I \cdot A_m \cdot \eta_m \cdot 0.771 \quad (1)$$

The monthly average energy, Eq. (2), is calculated by scaling the daily average energy (E_d) by the number of days in the month (D). This accounts for variations in month length, ensuring that the energy estimate accurately reflects the total production potential for the given month. For example, February with 28 days will yield a lower total than a 31-day month, assuming the same daily average.

$$E_m = E_d \cdot D \quad (2)$$

Eq. (3) describes the mean monthly average energy and represents the yearly average of the energy generated per month. It is calculated by summing the monthly energy outputs (E_m) for all 12 months and dividing the total by 12. This value provides a normalized metric that accounts for seasonal variations in solar irradiance, enabling a balanced assessment of the system's energy generation capacity throughout the year.

$$\bar{E}_m = \frac{\sum_{i=1}^{12} E_{m_i}}{12} \quad (3)$$

The number of modules, represented by Eq. (4) is required to meet the user's energy demand is calculated by dividing the customer's total energy consumption (C) by the mean monthly average energy ($\bar{E}_m$) generated by a single module. The result is always rounded up to ensure that the system generates at least the required energy. This approach guarantees that even with minor inefficiencies, the system can adequately meet the user's consumption needs.

$$N_m = \left\lceil \frac{C}{\bar{E}_m} \right\rceil \quad (4)$$

The system power (P_s) is the total power output of the photovoltaic system, represented in Eq. (5), calculated by multiplying the number of modules (N_m) by the module power (P_m) and dividing the result by 1,000 to convert it to kilowatts peak (kWp). The result is rounded to two decimal places for precision. This value represents the installed capacity of the system and serves as a key metric for comparing the system's potential output with the user's energy needs and regional regulatory requirements.

$$P_s = \mathrm{Round}\left(\frac{N_m \cdot P_m}{1000}, 2\right) \quad (5)$$

Eq. (6) shows the occupied area (A_t) represents the total physical space required to install the photovoltaic modules. It is calculated by multiplying the number of modules (N_m) by the module area (A_m), with the result rounded to two decimal places for accuracy. This metric is crucial for ensuring that the installation site has sufficient space to accommodate the required number of modules, which directly affects the feasibility of the system design for a given location.

$$A_t = \mathrm{Round}(N_m \cdot A_m, 2) \quad (6)$$

The total weight (W_t) of the photovoltaic system is calculated by multiplying the number of modules (N_m) by the module weight (W_m), as described in Eq. (7). This parameter is essential for assessing the structural requirements of the installation site, ensuring that the roof or support structure can safely bear the weight of the modules and maintain the system's integrity over time.

$$W_t = N_m \cdot W_m \quad (7)$$

The monthly energy generated (E_{mg}) represents the total energy produced by the photovoltaic system in a month. It is calculated by multiplying the monthly average energy (E_m) by the number of modules (N_m). This factor is calculated by Eq.(8) and provides a clear estimate of the system's output for a specific month and is a critical metric for comparing energy generation with the user's monthly consumption needs.

$$E_{mg} = E_m \cdot N_m \quad (8)$$

And last, Eq. (9) represents the average generation ($\bar{G}$) represents the annual average energy generated by the photovoltaic system. It is calculated by dividing the monthly energy generated (E_{mg}) by 12, providing a normalized value for the system's output across the year. The result is rounded to two decimal places for precision. This metric is essential for evaluating the system's long-term performance and comparing it against the user's average annual energy consumption.

$$\bar{G} = Round\left(\frac{E_{mg}}{12}, 2\right) \quad (9)$$

Simulation Process

Two sequences of simulations were conducted. In the first sequence, 10 simulations were performed with an increasing number of photovoltaic modules to observe the variation in other parameters under scenarios of growing energy demand. In the second sequence, 9 simulations were carried out considering the same energy consumption but with variations in geographic regions within the state of São Paulo, as Northwest, North, West, Central, Metropolitan Region of Campinas, Sorocabana, Baixada Santista, Greater São Paulo, and Northern Coastline. One city was selected per region to analyze the variation in solar irradiance intensity across the state.

3. Results & Discussion

Figure 1 shows the interface of the photovoltaic system simulator, displaying fields for data input such as name, state, city, and average monthly energy consumption. This initial configuration allows simulations to be customized based on specific user information.

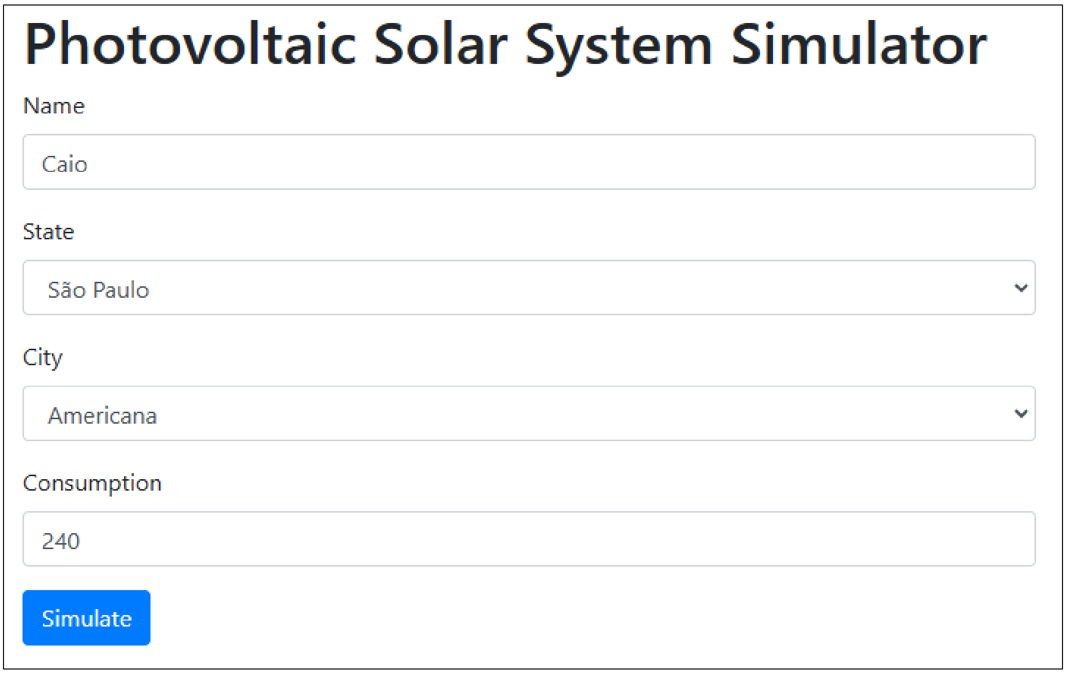

Fig 1: Interface of the photovoltaic system simulator.

Figure 2 presents the region selection interface in the photovoltaic system simulator. This feature allows users to choose the project's location, including information such as state and city. After selecting the city, the system automatically retrieves the corresponding geographical coordinates and obtains solar irradiation parameters from the Solarimetric Atlas. This functionality ensures that the calculations are based on accurate regional data, enabling a personalized and efficient sizing of the photovoltaic system according to the specific conditions of each location.

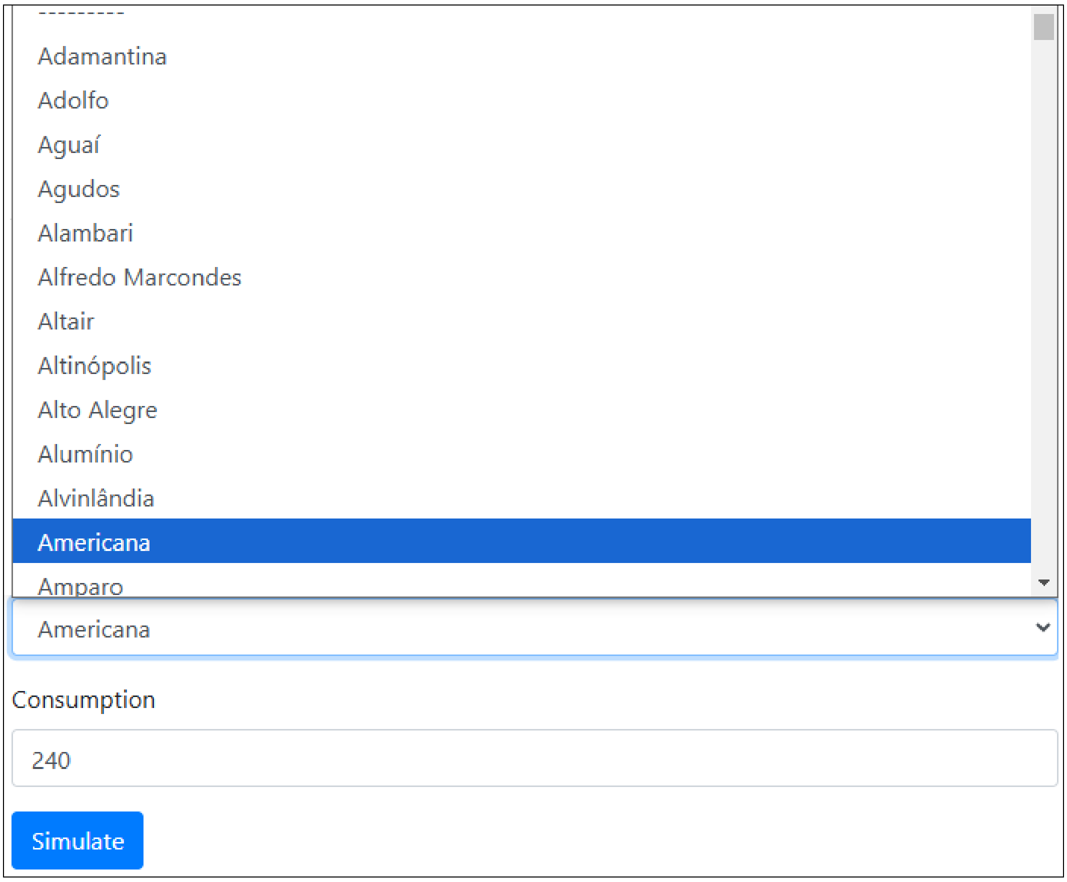

Fig 2: Interface for selecting regions

Figure 3 illustrates the data output screen of the photovoltaic system simulator. This interface presents the results of the system sizing, including detailed information such as system power, number of modules, occupied area, total weight, and average energy generation.

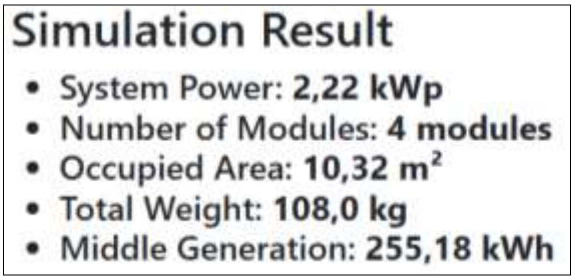

Fig 3: Example of the simulator's data output screen

Table 1 presents the parameters calculated by the photovoltaic system simulator for 10 distinct scenarios in the state of São Paulo. The data include system power (in kWp), the number of photovoltaic modules, occupied area (in m²), total weight (in kg), and average monthly energy generation (in kWh). The scenarios were defined to illustrate variations in system sizing, considering factors such as installed capacity and physical space requirements. These results demonstrate the simulator's ability to provide detailed and adaptable estimates for different regional conditions, contributing to the efficient planning of photovoltaic projects.

Table 1: Parameters calculated by the simulator

Simulations #	System Power (KWp)	Modules (N)	Occupied Area (m²)	Total Weight (kg)	Average Generation (KWh)
1	1.67	3	7.74	81.00	201.94
2	2.22	4	10.32	108.00	260.12
3	2.78	5	12.90	135.00	337.61
4	3.89	7	18.06	189.00	449.13
5	4.44	8	20.64	216.00	449.24
6	5.00	9	23.22	243.00	600.33
7	6.66	12	30.96	324.00	740.20
8	8.33	15	38.70	405.00	916.30
9	8.88	16	41.28	432.00	934.23
10	10.55	19	49.02	513.00	1209.30

Table 2 summarizes the parameters calculated by the photovoltaic system simulator for nine cities across different geographic regions in the state of São Paulo. These regions were chosen to represent variations in solar irradiance intensity, taking into account differences in latitude, climate, and topography. The simulations were conducted using the same average energy consumption (300 KWh) to analyze the impact of geographic variations on system performance. These results highlight the adaptability of the tool in tailoring photovoltaic system designs to diverse regional conditions, ensuring efficiency and optimal performance.

Table 2: Parameters calculated by the simulator by regions of state

Location (City)	System Power (KWp)	Modules (N)	Occupied Area (m²)	Total Weight (kg)	Average Generation (KWh)
São José do Rio Preto	2.78	5	12.90	135	333.26
Marília	2.78	5	12.90	135	325.03
Bauru	2.78	5	12.90	135	324.32
Araraquara	2.78	5	12.90	135	325.16
Ribeirão Preto	2.78	5	12.90	135	329.67
Sorocaba	2.78	5	12.90	135	308.88
Campinas	2.78	5	12.90	135	318.24
Santos	3.33	6	15.48	162	322.41
São José dos Campos	3.33	6	15.48	162	355.88

4. Conclusions

This study developed a software tool for sizing photovoltaic systems, leveraging the Django framework to provide efficient and precise simulations. By integrating real-world data from the Brazilian Solarimetric Atlas, the tool proved its accuracy and usability across diverse scenarios. It addresses critical challenges in the solar energy sector, such as under dimensioned and over dimensioned projects, by enabling users to customize calculations based on specific parameters and optimize system performance.

The simulations and validations conducted highlighted the tool's potential to streamline the design process for solar energy projects, contributing to cost savings and promoting the adoption of renewable energy. Despite its reliance on accurate meteorological data and ideal conditions, the tool represents a significant step towards democratizing access to solar energy solutions and fostering sustainability in energy generation.

The tool relies on precise and up-to-date meteorological data. Additionally, the simulations consider ideal installation conditions, and practical applications may vary due to local factors.

Future work will focus on incorporating additional features, such as real-time data integration and extended compatibility with other renewable energy sources, to further enhance its capabilities and application scope.

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