VIRTUAL LABORATORY FOR TEACHING PHOTOVOLTAIC SOLAR ENERGY

https://doi.org/10.56238/sevened2024.041-003

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ABSTRACT
This paper presents the development of a computational platform for teaching and designing photovoltaic generation, both autonomous and grid-connected. The platform uses meteorological data and tools that allow the dimensioning of active power and technical-economic and environmental assessment. The developed methodology allows the user to have a friendly interaction with the platform with graphical and numerical visualizations. To validate the developed computational program, a numerical experiment was carried out, based on the consumer loads of a residence, which made it possible to prove its applicability as a tool for students and designers of photovoltaic systems.

Keywords: Photovoltaic solar energy. Virtual teaching laboratory. Photovoltaic generator design. Computer simulation.

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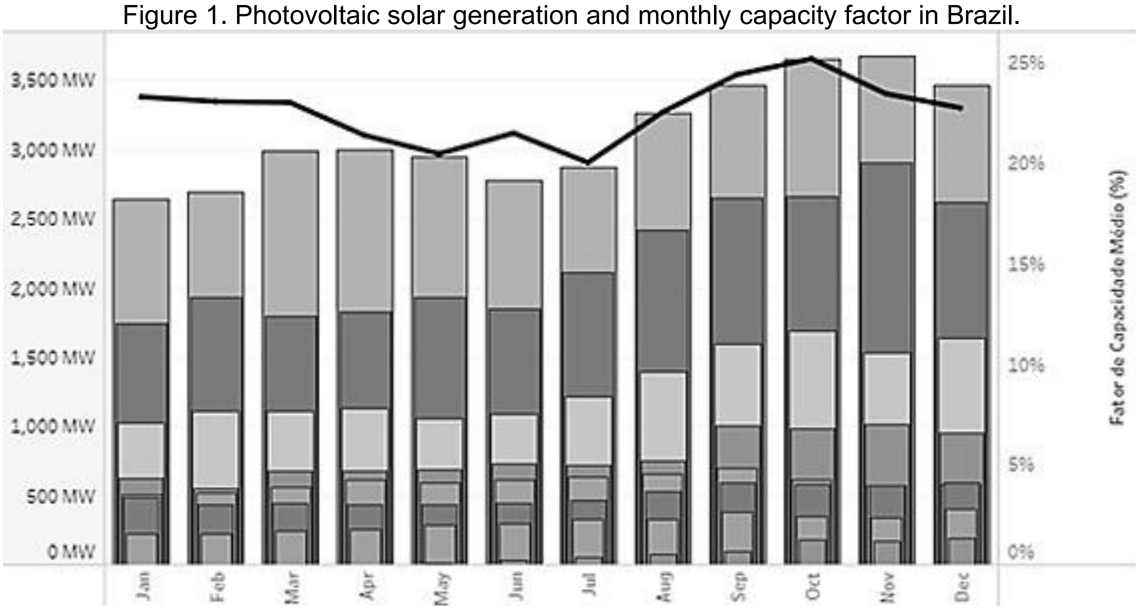
INTRODUCTION

Distributed generation (DG) has shown steady growth over the years, consolidating itself as a sustainable alternative for the supply of electricity, in a generation arrangement close to the final consumer (ACKERMANN et al., 2001). DG is characterized mainly by the use of renewable sources and is aligned with the global consensus on energy transition in reducing carbon emissions and contributing to the mitigation of environmental impacts (BOYLE, 2012).

Figure 1 shows the growth in installed capacity of solar photovoltaic generation (SPG) from 2015 to 2024, according to data from the National Electric System Operator (ONS). In this sense, SPG has grown due to its modularity, ease of installation and low maintenance cost, being used both to provide electricity to isolated regions and to consumer units connected to the public grid.

Figure 1. Photovoltaic solar generation and monthly capacity factor in Brazil.



Source: ONS - National Electric System Operator.

In Brazil, the photovoltaic solar energy market has shown significant growth in recent years. In 2024, according to ANEEL's Micro and Mini Distributed Generation (MMGD) report, Brazil reached 34 GW of installed DG capacity, benefiting more than 4.2 million consumers and covering more than 3 million residential and business installations (ANEEL, 2024). This advance has contributed significantly to the expansion of sustainable energy production in the country and to the reduction of electricity costs for agents that adopt MMGD systems.

For comparison purposes, in 2022, Brazil had 20 GW of installed capacity, representing a 70% increase in the number of micro and mini generators in just two years. The result reflects the implementation of growth-friendly policies, such as the state tax exemption introduced in 2015 and the Legal Framework for Distributed Generation approved in 2021, through Law 14,300, consolidating solar energy as one of the main renewable sources in the country.

In this context, computational teaching and design platforms stand out as attractive tools for students and designers, since they allow the implementation and development of projects, simulations of electrical power systems and cover all components of MMGD systems (PINHEIRO, C.; RIBEIRO, M., 2005).

These platforms enable implementation at any scale and offer designers a low-cost solution for learning and/or design, enabling everything from sizing to commissioning a plant, for example a GFV, created using a specialized framework. These computational teaching and design environments are attractive to engineering students and professionals, who can create, design and simulate various photovoltaic generator configurations (OCHS, D. S.; MILLER, R. D., 2015).

Considering the teaching and design platform environment, this paper presents the development of a specialized software for teaching and designing PV, focusing on MMGD systems. The platform was designed to assist engineering students and professionals in learning and designing photovoltaic plants, incorporating technical criteria that meet current standards and the dimensioning of essential electrical parameters of a PV plant.

Parameters such as generated and consumed power, open circuit voltage (VOC), short-circuit current (ISC), module operating temperature, voltage and current at the maximum power point ($Vmpp$ and $Impp$), losses in the PV system, solar irradiation, autonomy and other parameters used in the study and design of GFV are essential to guarantee performance, reliability and compliance with the technical requirements of micro and mini generation, allowing learning and development of optimized projects for different geographic and climatic conditions.

THEORETICAL FRAMEWORK

PV generation occurs through the photovoltaic effect, in a process of capturing photons from the spectrum of sunlight incident on a specific area (A) of one or more photovoltaic cells, manufactured from semiconductor materials, such as silicon, which can be doped with Boron (B) and Phosphorus (P) atoms to form P and N type semiconductor materials, thus having the PN junction of the PV cell (DIMROTH; KURTZ, 2007).

Thus, the interaction of sunlight with the depletion zone formed in the PN junction, characterized by the separation of spatial charges in the semiconductor material, captures the energy of the photons ($\hbar\omega$) and generates electron-hole pairs that result in the creation of voltage and electric current when there is a consumer electrical circuit at the cell terminals.

Otherwise, cells connected in series form a PV module, which has specific electrical characteristics that depend on the semiconductor material used to manufacture the cells. The most common materials are polycrystalline and monocrystalline silicon, which differ in efficiency, cost and performance under certain solarimetric conditions.

Some electrical parameters that appear on the module nameplate are open circuit voltage (VOC), short circuit current (ISC), voltage and current at the maximum power point ($Vmpp$ and $Impp$), nominal efficiency (η), among others.

These parameters are determined under standard test conditions (STC), which correspond to an irradiance of 1000 W/m², cell temperature of 25°C and air mass of 1.5. However, field operating conditions differ from STC, as factors such as ambient temperature, irradiance variability, partial shading, orientation and tilt of the modules significantly influence their performance, and can alter the efficiency of the system and directly impact the energy generated (PINHO; GALDINO, 2014).

Depending on the electrical load consumed, just one PV module may not be sufficient to provide electrical power, which leads to the need for a GFV with adequate power, composed of solar modules connected in series and/or parallel configuration, forming M strings, with each string formed by N modules connected in series.

ELECTRICAL AND ENERGY PRODUCTION PARAMETERS

The output power of a GFV is calculated from several factors and must take into account the module temperature and efficiency losses resulting from dust accumulation, partial shading, losses due to voltage drops in the cabling and connections, among others (BALFOUR, J.; SHAW, M.; NASH, N. B, 2013). It is important to take into account the operating temperature of the photovoltaic module, denoted by TC ($°C$), which can be estimated with the empirical equation given by (ABBES et al., 2012):

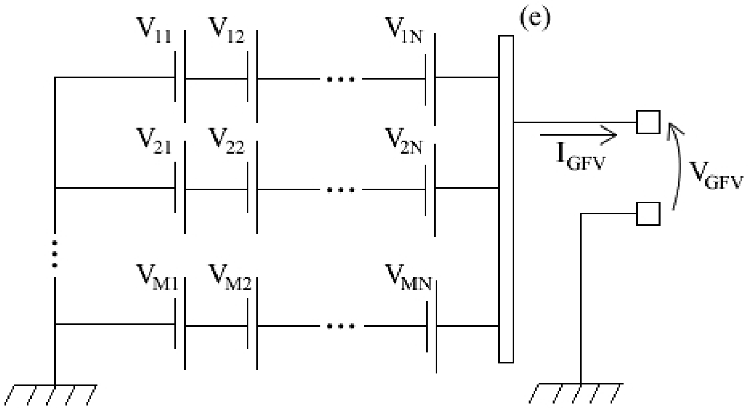
$$T_C = 30 + 0{,}0175 \times (G_i - 300) + 1{,}14 \times (T_A - 25) \quad (1)$$

Equation 1 provides an estimate of the FV module operating temperature (TC in $°C$), G_i the incident solar irradiance in W/m² and T_A the ambient temperature in $°C$. Thus, it is possible to incorporate the impact of the operating temperature in the calculation of the FV module active power (P_{mpi}), based on the module peak power at STC conditions, ($P_{mp\,ref}$) and expressed in watt-peak (Wp). The following expression allows the calculation of P_{mpi}:

$$P_{mp_i} = P_{mp_{ref}} \times \frac{Gi}{G_{ref}} \times [1 + \gamma_{mp}(T_C - T_{ref})] \quad (2)$$

where G_{ref} is the reference irradiance = 1000 $W/m2$, and Υ_{mp} is the coefficient of variation of power with temperature ($1/°C$). The electrical behavior of a GFV, with M strings in parallel and N modules connected in series per string, can be represented as shown in Figure 2.

Figure 2. Electrical model of a photovoltaic generator.



Source: Prepared by the authors.

In addition to active power, the operating voltage (V_{mpi}) of the FV module can be adjusted to reflect actual operating conditions. The adjustment is based on the reference voltage at the maximum power point (V_{mpref}), the voltage variation coefficient (β_{mp}) as a function of temperature ($°C{-}1$) and the module and reference operating temperatures, according to the equation:

$$V_{mp_i} = V_{mp_{ref}} \times [1 + \beta_{mp}(T_C - T_{ref})] \quad (3)$$

The total output power of a GFV (P_{GFVref}), configured with M strings in parallel and N modules connected in series per string, is given by:

$$P_{GFVref} = P_{mp_{ref}} \times M \times N \quad (4)$$

By combining equations 2 and 4, the GFV operating power, considering specific temperature and irradiance conditions, is:

$$P_{GFV} = P_{mp_i} \times M \times N \quad (5)$$

The total output voltage of the GFV (V_{GFV}) can be calculated considering the operating voltage of the modules and the quantity in series (N):

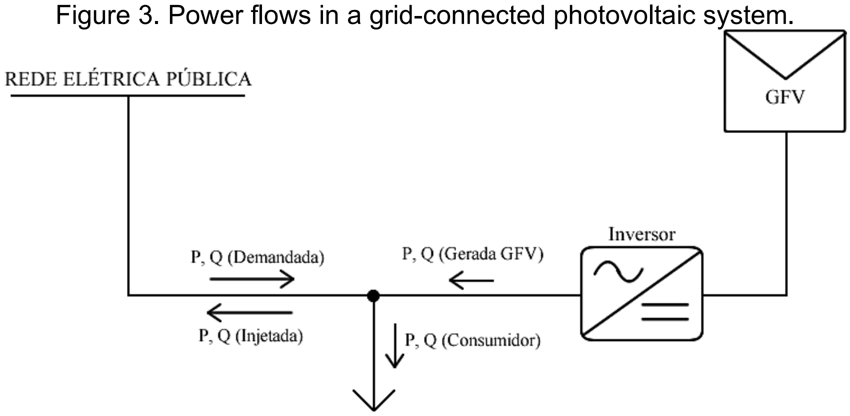
$$V_{GFV} = V_{mp_i} \times M \times N \quad (6)$$

The inverter's active output power ($P_{out\ inv}$) considers its efficiency (η_{inv}) and losses due to external factors η_{ext}, given by:

$$P_{o_{inv}} = P_{GFV} \times \eta_{inv} \times \eta_{ext} \quad (7)$$

Equations 1 to 7 allow the calculation of the performance of a PV system close to real conditions, considering losses and efficiency, ensuring a more precise dimensioning of the PV generator and inverter according to the electrical parameters of the modules and equipment. Figure 3 illustrates the power flows in a PV system, with P and Q representing the active and reactive power, demanded or injected into the grid.

Figure 3. Power flows in a grid-connected photovoltaic system.



Source: Prepared by the authors.

Among the sizing parameters of a PV solar plant, the energy balance produced by the plant is essential to estimate the performance of the systems and evaluate the impact of factors such as irradiance, losses and growth in the consumption profile. The energy balance expressions allow modeling energy generation and consumption under real operating conditions, incorporating loss rate, load growth and system efficiency over time.

The electrical energy generated by a GFV under ideal conditions, denoted as E_{GFVref}, can be calculated based on the nominal power (P_{GFVref}), according to equation 4, considering the minimum monthly full sunlight hour (HSP_{min}) and the number of days in a month (N_d), according to:

$$E_{GFV_{ref}} = P_{GFV_{ref}} \times HSP_{min} \times N_d \quad (8)$$

Under actual operating conditions, the generated energy ($EGFV$) is adjusted to consider the average monthly full sunlight hour ($HSPmed$), as follows:

$$E_{GFV} = P_{GFV} \times HSP_{med} \times N_d \quad (9)$$

The energy generation efficiency of the PV plant is reduced due to factors such as high temperature, dirt on the cells, electrical losses, inadequate inclination, unfavorable orientation and shading (BALFOUR et al., 2013). Considering the main losses in a PV plant, such as temperature losses (Δ_{PT}), dirt losses (Δ_{PS}), and electrical losses (Δ_{PC}), the energy generated with losses is given by:

$$E_{GFV} = E_{GFV_{ref}} \times (1 - \Delta P_T) \times (1 - \Delta P_S) \times (1 - \Delta P_C) \quad (10)$$

Furthermore, the degradation of the GFV, i.e., loss of efficiency in energy conversion, affects the efficiency of the generator as a whole. The annual energy generated can be considered with an annual efficiency loss rate (i_{PE}), which can be expressed as:

$$E_{GFV_{ANUAL}} = \frac{E_{GFV}}{(1 + i_{PE})^t} \quad (11)$$

The energy balance of a PV generation plant is essential for planning energy systems, aiming to meet the current load and future growth. Thus, the energy demanded ($EDEM$) in a given year is calculated from the initial energy demanded ($EDEM0$), weighted by an annual consumption growth rate (iAC) given the period t, as follows:

$$E_{DEM} = E_{DEM_0} \times (1 + i_{AC})^t \quad (12)$$

The analysis, using equations related to electricity generation and demand, as well as loss factors and operational and environmental conditions of the GFV, is essential for the integration of photovoltaic systems in projects of different scales, ensuring that they meet the technical and economic objectives of the project.

ECONOMIC ANALYSIS OF PHOTOVOLTAIC GENERATION

The decision to implement a GFV project requires an assessment of the financial viability of the investment. This analysis is based on economic indicators and the value of the asset over time, applying methods that project the costs and benefits during the useful life of the system, which can be analyzed using software synchronously with the technical project for small or large plants, as highlighted by Parente (2017).

The monetary savings resulting from FV generation come from the electrical energy generated by the system (E_{EC}), which is equal to the energy generated in the GFV ($E_{GF}V$), E_{EC} = E_{GFV}. The total project cost (C_{totINV}) includes the investment in equipment and can be expressed as (PARENTE, 2017):

$$C_{tot_{INV}} = \sum_{i=1}^{N} C_i + C_{mob} + C_{proj} \quad (13)$$

In which, Ci represents the individual costs of the plant equipment, C_{mob} and C_{proj} consider the expenses with installation labor and electrical design. However, throughout the useful life of the FV system, it is necessary to consider the operation and maintenance (O&M) costs, such as cleaning, replacement of modules or inverters and other services. The O&M cost, adjusted by the cost inflation rate (TIC) (PARENTE, 2017), is:

$$C_{O\&M} = D_{O\&M_i} \times (1 + TIC)^t, \quad t = 0,1, \dots, T \quad (14)$$

where $D_{O\&Mi}$ is the annual O&M expense and T is the maximum analysis time.

The gross financial benefit (R_F), given in current currency, is calculated based on the electricity generated (E_{EC}) and the electricity tariff (d_{TE}), adjusted for inflation over time, as follows:

$$R_F = E_{EC} \times d_{TE} \times (1 + TIC)^t, \quad t = 0,1, \dots, T \quad (15)$$

Net income (R_L) is obtained by subtracting O&M costs from the gross benefit and provides the net result of the financial operation for the investment in the photovoltaic solar plant, given in the form of:

$$R_L = R_F - C_{O\&M} \quad (16)$$

GFV also contributes to the reduction of greenhouse gas emissions, such as carbon dioxide (C_{O2}). The environmental assessment, available on the platform, is carried out by calculating the volume of C_{O2} avoided (V_{CO2}), which is obtained by multiplying the energy generated in the PV system by the mitigated C_{O2} emission factor (T_{CO2}), resulting in:

$$V_{CO_2} = E_{GFV} \times T_{CO_2} \quad (17)$$

Thus, evaluating the recurring expenses and benefits throughout the useful life of the PV system, as well as the positive impact on the environment, through the reduction of CO2 emissions, allows the designer to make an adequate assessment regarding the project, implementation and maximization of the economic return, promoting efficiency in the use of natural resources.

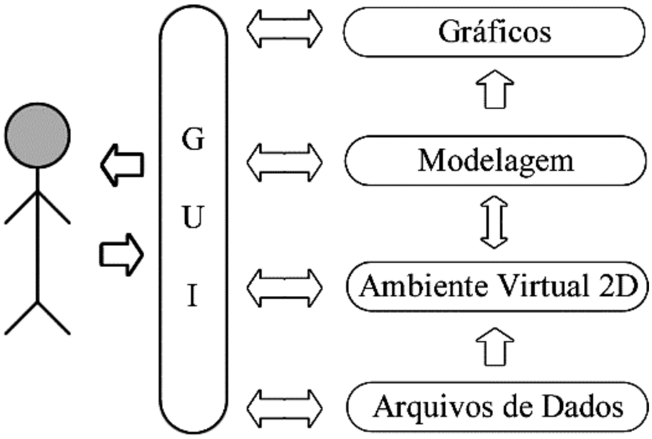
METHODOLOGY

The developed computational tool has an architecture composed of three main modules: Graphical User Interface (GUI), two-dimensional virtual environment and a FV System (PFS) modeling module. These modules interact in an integrated manner, providing the user with a complete PV System analysis and configuration experience, with visualization of the system's physical connections through single-line diagrams, representing modules, inverters and cabling, facilitating the understanding of the interconnections between the elements.

The GUI interface allows simplified access to the tool's main functionalities through organized menus and panels. The GUI allows the user to enter, store and retrieve information in a dedicated database, in addition to configuring parameters of the system components in an intuitive manner.

The modeling module is responsible for collecting the necessary data and performing PV System simulations, solving the equations related to the system with the various meteorological and electrical parameters. The simulation results feed the virtual environment and allow the user to visualize the system's performance in different scenarios. Figure 4 shows representations of the platform modules.

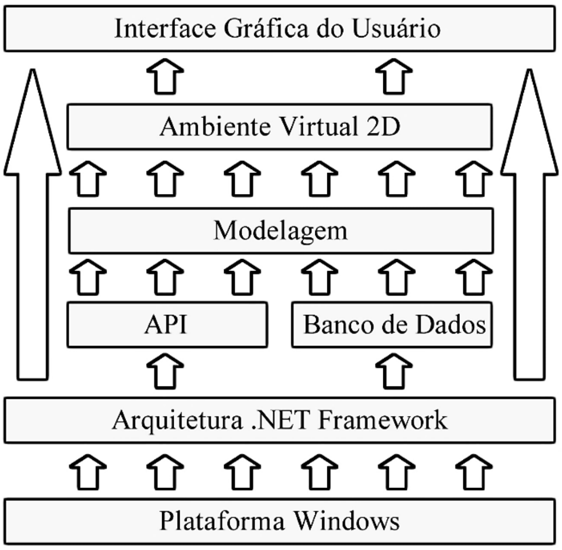
Figure 4. Computational platform modules.



Source: Prepared by the authors.

The structure of the computing platform uses a set of libraries and APIs of the C# language to allow fluid interaction between the internal components and the user, through the GUI interface. The architecture also facilitates the access and manipulation of an integrated database, which stores essential information for the SFV project in its own file in “.sfv” format. Figure 5 illustrates the proposed architecture, highlighting the construction of the platform in the Windows operating system, using the capabilities of the .NET Framework and the APIs provided by the C# language (MICROSOFT, 2000).

Figure 5. Computing platform architecture.



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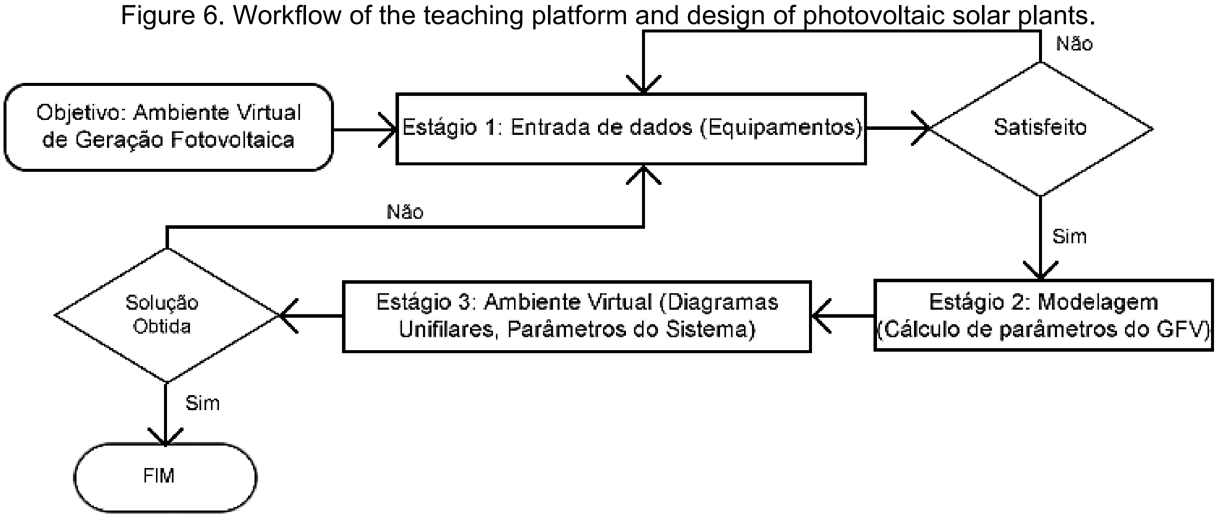
The .NET Framework architecture provides robust support for the geometric representation of SFV, allowing the execution of basic operations, such as the displacement and manipulation of models in the virtual environment. These operations are implemented directly through the C# APIs, which provide the necessary functionality to ensure efficient platform performance.

The platform database plays a central role in enabling the user to select equipment according to the specific requirements of the PV project. Developed using the C# architecture, the simulator's internal database employs the Advanced Encryption Standard (AES) to ensure the security of stored data from manufacturers and advanced users, using the RFC2898 library, which implements a password-based key generation scheme with a pseudo-random number generator to increase data security. This approach allowed the creation of a custom data structure within the simulator, with the aim of storing detailed information about PV components: modules, batteries, charge controllers, inverters, circuit breakers and other accessories. The workflow for creating the virtual PV generation environment is organized into three main stages, as shown in the flowchart in Figure 6.

Figure 6. Workflow of the teaching platform and design of photovoltaic solar plants.



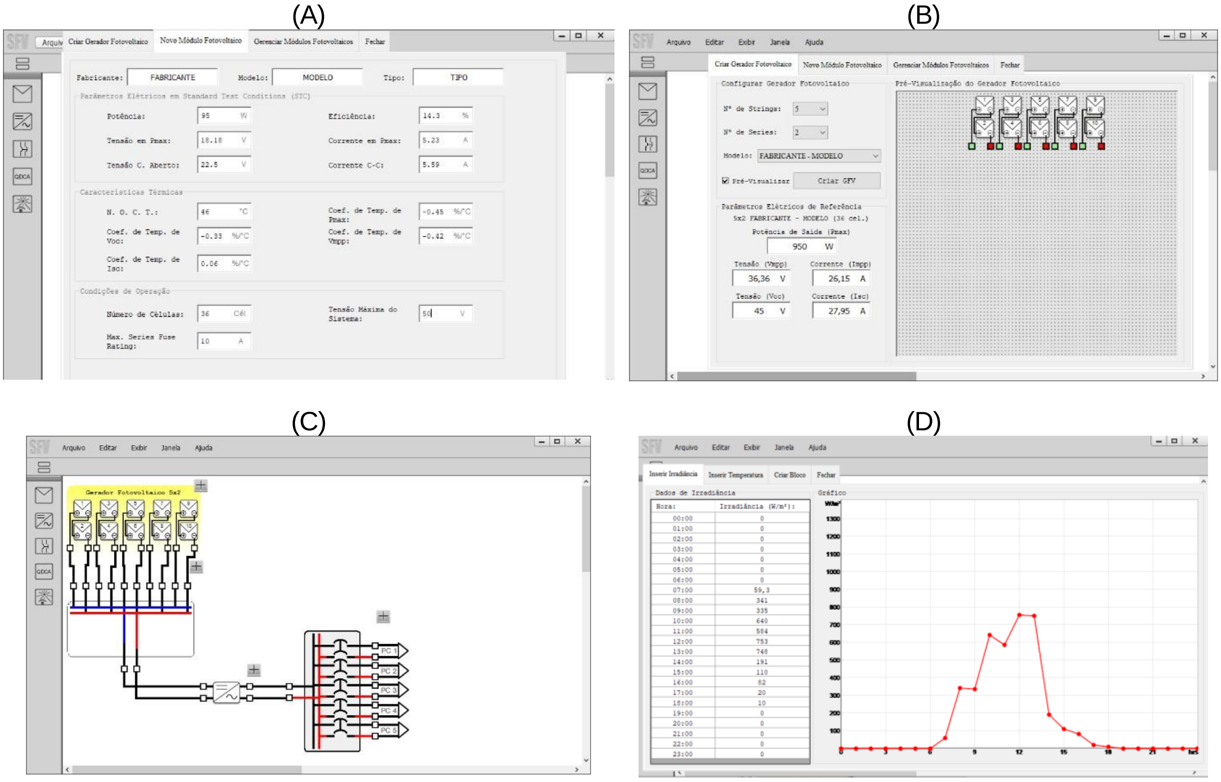
Source: Prepared by the authors.

Stage 1 includes input of data on PV generator equipment, technical parameters, costs, meteorological data, economic rates and load demand. Stage 2 is responsible for calculating generator parameters, losses and power flow to the system output point. In stage 3, the user can view and interact with the system, perform operational tests, receive safety alerts, perform economic analysis and assess the mitigation of pollutant gas emissions from the system.

RESULTS AND DISCUSSIONS

The methodology proposed in this article demonstrates a solution for simulations in virtual environments of GFV. The flexibility of the tool allows the user to select registered equipment from photovoltaic systems or insert new items. In addition, it is possible to modify the registered data on demand. Figure 7 shows the graphical interface of the educational platform for modeling photovoltaic solar systems.

Figure 7. Educational platform for modeling photovoltaic solar systems.

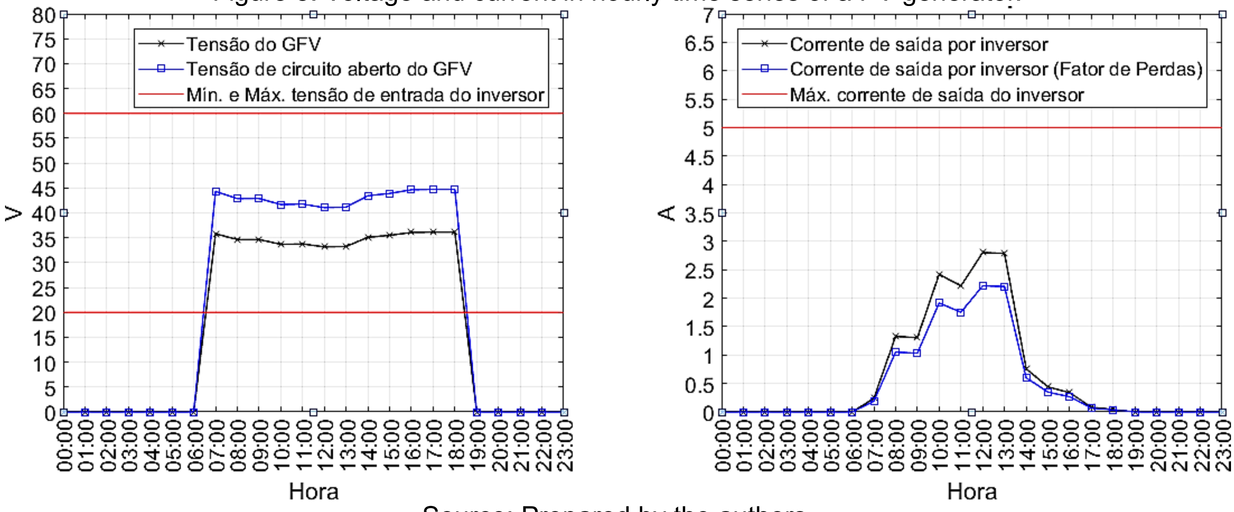


Source: Prepared by the authors.

The platform consists of two main modules, one for stand-alone photovoltaic systems (SFVA) and the other for grid-connected systems (SFCR), both developed to size photovoltaic generators in two different DG configurations. The calculation of the active power of the PV generator is performed using a matrix method, as per section 2, in which M represents the number of strings and N the number of modules connected in series. The generator reference parameters are displayed directly in the interface, as per Figure 7, with automatic alerts in case of inconsistencies, such as if the maximum generator voltage exceeds the supported limit of the modules.

Another feature of the platform is the simulation of photovoltaic generators, where the user can input meteorological data, such as irradiance and temperature, which are stored in the internal database for use in the simulation, as shown in Figure 7-D. From this data, the modeling of the PV generator is performed together with the other equipment, DC string boxes, DC/AC inverters, and AC string boxes, as shown in Figure 7-C, and the results can be viewed in the virtual environment using probe-type instruments, ammeters and voltmeters, or in detailed graphs, as shown in Figure 8.

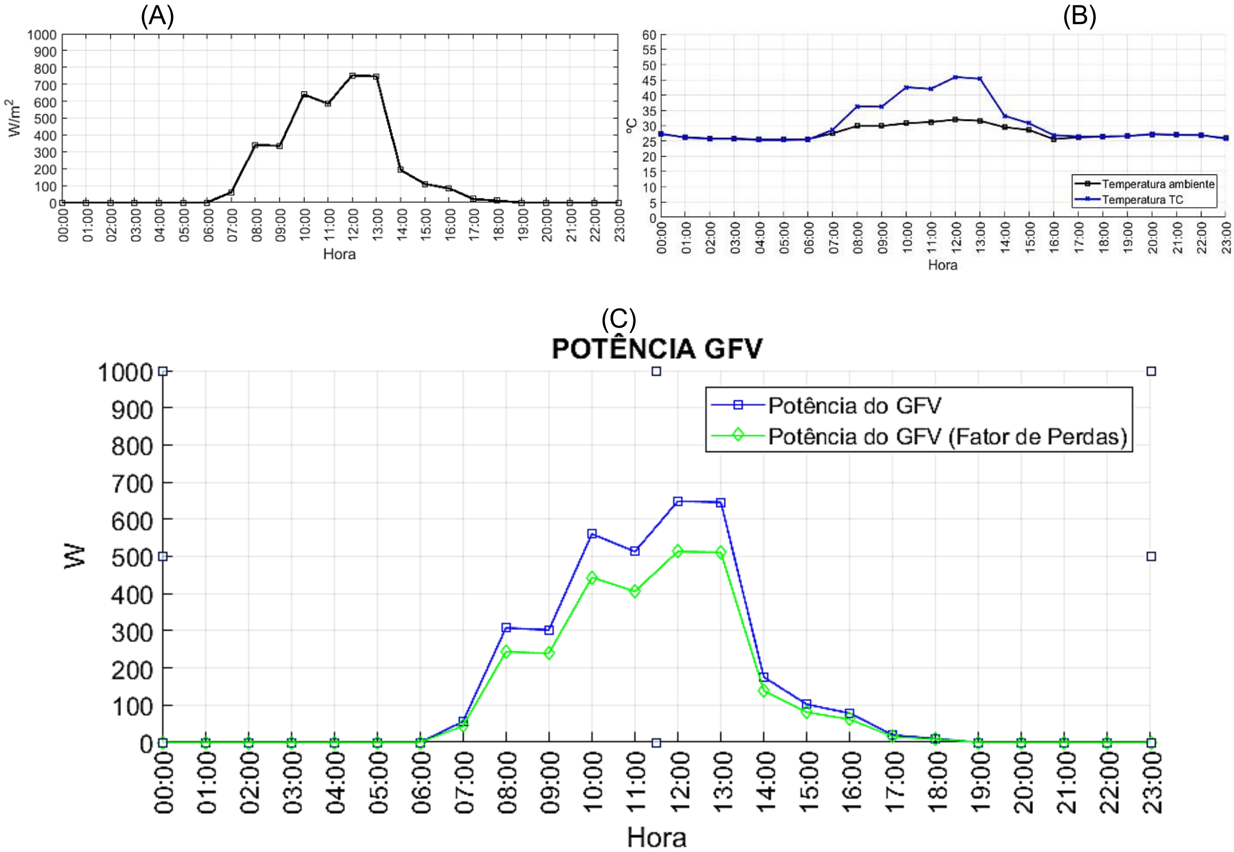
Figure 8. Voltage and current in hourly time series of a PV generator.



Source: Prepared by the authors.

The computational platform allows the calculation of the active output power of the PV generator, based on variables such as irradiance, ambient temperature, module temperature and loss indices, considering operating scenarios without losses and with losses, as shown in Figure 9.

Figure 9. Irradiance curve (A), TC temperature (B), and active power (C) of a GFV.



Source: Prepared by the authors.

Furthermore, as a computational tool for teaching and designing PV generators, it provides a remarkable resource for automatically checking the parameters of the equipment and assists in verifying the compatibility and performance of the designed PV generator, considering the technical limits of the equipment and current technical standards. An example of this functionality is shown in Figure 10, in which some parameters of the PV generator were automatically checked.

Figure 10. Verification system on the console.

```
[Verificado] Potência de surto do sistema e potência de surto de saída do inversor.
[Verificado] Potência instalada do sistema e máxima potência de saída do inversor.
[Verificado] Corrente de saída do inversor.
[Verificado] Tensão de entrada do inversor.
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Source: Prepared by the authors.

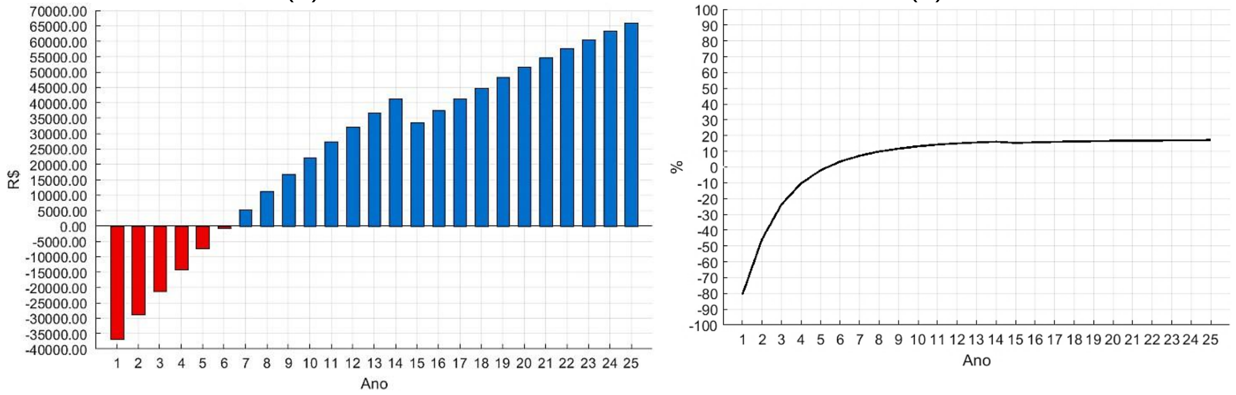
The computational platform has a module that allows the calculation of daily energy consumption ($\boldsymbol{E_{CD}}$), being $\boldsymbol{E_{CD}} = \sum \mathbf{23}\ \boldsymbol{E_{Ci}}$, where $\boldsymbol{E_{Ci}}$ represents the energy consumed in each hour of the day in the form of a vector $\boldsymbol{E_{Ci}} \in \mathbb{R}^N$ to N equal to 24 h. Load increases in the energy demanded from the generator are adjusted based on the specified annual growth factor, as per equation 12. The energy demanded from the FV generator is given by the annual energy consumption $\boldsymbol{ECA}$, corrected by a load increase rate in the form of $E' = E_{CA} \times (1 + i_{AC})^t$, the energy demanded being corrected.

To size the PV generator, the monthly ($\boldsymbol{E_{CMREF}}$) and daily ($\boldsymbol{E_{CD}}$) reference energy consumed are considered, the minimum and average $\boldsymbol{HSP}$ values, loss factors ΔPT, ΔPS and ΔPC for calculating the global vector loss factor ($\boldsymbol{I_{FP}}$) and the vector GFV power ($\boldsymbol{P_{GFV}}$) from the minimum $\boldsymbol{HSP}$, where $\boldsymbol{P_{GFV}} = \boldsymbol{I_{FP}}(50\% \times \boldsymbol{E_{CMREF}})/\boldsymbol{HSP_{min}}$. In this expression, in addition to the parameters already declared, a safety factor of 50% is considered for seasonal variations in solar radiation.

The power data include the daily and annual active power profile of the FV generator with and without losses, calculated through the efficiency and annual degradation indexes. These values feed the energy production data and allow the economic analysis of the system. The calculation of the Net Present Value (NPV) considers a discount rate t_d and the Internal Rate of Return (IRR) reflects the financial viability of the investment, as per the example of a calculation performed on the computational platform, shown in Figure 11.

Figure 11. Cumulative NPV and IRR of a modeled solar PV plant.

(A) VPL (B) TIR



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CONCLUSION

The developed computational platform proved to be an efficient and versatile tool for planning, simulating and analyzing photovoltaic systems, with the potential to meet the demands of teaching and development in the area. The user-friendly interface allows easy access to technical and electrical parameters, PV generator sizing and interactive diagrams for visualization and operation of the designed system.

The possibility of simulating real conditions, including faults and weather variations, contributes significantly to the technical and economic assessment of GFV projects. The proposed virtual environment offers detailed information, such as consumption and generation profiles at different time scales, helping to identify optimizations in the system.

The incorporation of loss factors and local conditions in the sizing increases the accuracy of the calculations, while the economic analysis adds value to the decision-making process. In this way, the platform stands out as an integrated solution for sustainable solar photovoltaic generation projects.

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