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FOTODIM—Software for Sizing of Photovoltaic Systems

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Abstract

This study addresses the development of a computational tool for the sizing of photovoltaic systems interconnected to the grid (grid-tied) and isolated (off-grid) systems. The calculations for the sizing were obtained from the CRESESB Engineering Manual for Photovoltaic Systems, the GREENPO Photovoltaic Systems Technology, Design and Installation Manual, and the BLUESOL Solar System Introduction Digital Book. With knowledge of the latitude, longitude and altitude data of the site, the tool calculates the angle of the modules for better absorption of the photovoltaic radiation. For systems connected to the grid, it is also necessary to provide information on the consumption of the building to be serviced by the photovoltaic system. For isolated systems, in addition to information on the site, it is necessary to know the demand and consumption of the building. Decision-making criteria are based on economic analysis, according to indexes such as Net Present Value (NPV), Internal Rate of Return (IRR), and Discounted Payback. The screens developed for the sizing tool and examples of sizing of both photovoltaic systems are presented as results, through tables and graphs. The developed software is reliable, and all calculations have theoretical basis.

Keywords: software development, solar energy, sizing photovoltaic systems

1. Introduction

The world's population may increase by roughly 1.5 billion people, reaching a milestone of nearly 8.8 billion by 2035. During this period, the gross domestic product (GDP) is expected to grow more than double, with one fifth of this growth coming from the increase of the population and four fifths, from improvements in productivity (BP Energy, 2016).

By 2030, energy consumption in developing countries is estimated to be 69% higher compared 2010, with an average growth of 2.7% per annum, accounting for 65% of the world's consumption, compared with 54% in 2010 (Kaygusuz, 2012).

The progressive growth of the world's population tends to raise levels of per capita consumption of resources, leading to a downward trend in the availability of natural resources. With the increasing urbanization and industrialization of the countries, the search for energy increases, pressing the administration of the governments to direct the plans of expansion of energy with exercises towards the sustainability (Heller, Espinasa, & Paredes, 2016; Singh, Vats, & Khanduja, 2016).

By 2035, renewable energy sources are expected to account for one quarter of the global primary energy growth and more than one third of the global energy generation growth, and may increase to 16% in energy generation, if technological and policy actions such as agreements enacted at COP 21, in Paris, are carried out (BP Energy, 2016).

Following the growth of its respective source, photovoltaic solar energy and solar thermal energy may contribute up to 27% for the world's electricity production by 2050 (IEA, 2014).

The largest domestic electricity supply source currently in Brazil is hydropower, accounting for 70.6% (BEN, 2014).

The construction of dams for electricity generation has been facing strong environmental restrictions and energy security policies, mainly in the Amazon Rainforest, which poses risks to the construction of a solid energy matrix, a situation that forces the use of non-renewable sources to supply the demand (Freitas & Soito, 2011; Pereira et al., 2012; Prado Jr., 2016; Ribeiro et al., 2016).

Decentralized power generation can become a viable alternative to meet consumer demand and reduce transmission and distribution grid costs (Mohajeri et al., 2016). This generation can be achieved by means of the installation of photovoltaic panels, which is already a reality in Brazil, albeit with little relevance. The IEA (2014) describes that solar energy is one of the renewable energy resources with the highest potential and may be the largest world source of electricity by 2050.

Market forecasts for photovoltaic modules are currently very optimistic, with some going well beyond what was estimated for the current technology situation in both developed and developing countries. Due to the growth of grid-tied installations in homes, the need arises to optimize the sizing of photovoltaic generation systems, as well as selection of efficient devices, with knowledge of all the costs involved and subsequent return on invested capital.

To provide users with a versatile and intuitive calculation tool, "FOTODIM" software was developed. Its objective is to design Grid-tie and Off-Grid photovoltaic systems, considering technical and economic criteria. The development of the computational tool was performed using MATLAB software (Matrix Laboratory, Mathworks, Inc., version R2013a). The software has a database of equipment, which will be used by the user for the design of the photovoltaic system, and a database of solar radiation from some cities of the State of Paraná. It is possible to add new equipment and register new locations.

2. Photovoltaic Solar Energy

The direct generation of electricity using solar energy is performed by photovoltaic modules. Photovoltaic cells are responsible for converting energy.

Through the photovoltaic effect, the cells absorb the available photons from the solar radiation and convert the energy from the sun into direct current. Photovoltaic technology in recent years has stood out among energy sources within the renewable matrix (REN21, 2012).

Photovoltaic generation systems can be formed in two ways: generators connected to the local transmission grid (grid-tied) and isolated grid generators (off-grid), the latter being often used in places where the transmission grid is inaccessible or for reasons of technical and/or financial feasibility.

Figure shows a Grid-tie photovoltaic system.

Figure 1. Grid-tie photovoltaic system

Note. (1) Photovoltaic modules; (2) Grid-tie inverter: the direct voltage generated by the photovoltaic panel is converted into AC voltage; (3) The voltage converted by the inverter passes through the bidirectional meter, which measures the energy consumption and the amount of energy injected into the grid; (4) A part of the energy generated is consumed by the equipment present in the building; (5) The surplus of the energy generated is injected into the concessionaire's grid.

Source: MaxiSolar, 2016.

Grid-tied and off-grid systems have equipment that can be specific to each application. Regardless of system configuration, however, PV modules and inverters are common uses in both systems.

In the systems connected to the grid, photovoltaic modules that generate the energy in direct current are used, as well as inverters that convert this energy into alternating current, synchronizing and injecting it to the grid.

Off-grid systems use the same equipment as the grid-tied systems plus some that are specific for this application. These include charge controllers and power storage systems (usually composed of lead-acid batteries).

Figure presents an off-grid photovoltaic system.

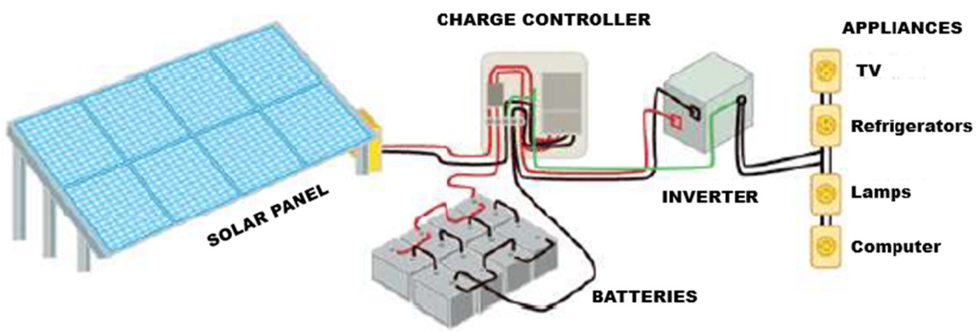

Figure 2. Off-grid photovoltaic system

Source: MaxiSolar, 2016.

Before arriving at the AC or DC charge (if any), the energy generated by the photovoltaic panel in off-grid systems passes through the charge controller, which is responsible for distributing the power generated between the battery bank and the inverter, as well as protecting the batteries from overvoltage or excessive discharge.

During the morning and afternoon periods, the charge controller charges the battery bank while sending the generated energy to the inverter, which, in turn, feeds the equipment that make up the AC charge. Because there is no power generation in the photovoltaic panel during nighttime, the controller cuts off the connection to the panel. The same happens in the morning and afternoon periods, when there is high cloudiness and the solar radiation index is low, and the voltage generated by the lower panel can be the one used by the DC or AC charge. In this case, to supply the charge, the controller sends power from the battery bank to the inverter (in case it is an AC charge) or directly to the DC charge. If due to an eventuality or design defect, the battery bank fails to meet the demand during these periods, reaching a limit discharge depth, the controller cuts off the connection to the inverter (AC charge) and the DC charge in order to protect the batteries.

3. Components of a Photovoltaic System

3.1 Photovoltaic cells

Table presents the commercially available photovoltaic cell technologies and some of their respective characteristics.

Table 1. Characteristics of photovoltaic cells

Material	Laboratory efficiency (%)	Production efficiency (%)	Efficiency due to serial production (%)	Area required for 1 kW_p (m^2).
Silicon (c-Si)	24.7	18	14	5-8
Silicon (m-Si)	19.8	15	13	7-9
Amorphous silicon	13	10.5	7.5	13-20
CIS	18.8	14	10	8-10
CdTe	16.4	10	9	9-11

Source: Adapted from BLUESOL, 2016; REN21, 2012; EPIA, 2011.

Figure 3 shows a diagram of the distribution of photovoltaic technologies.

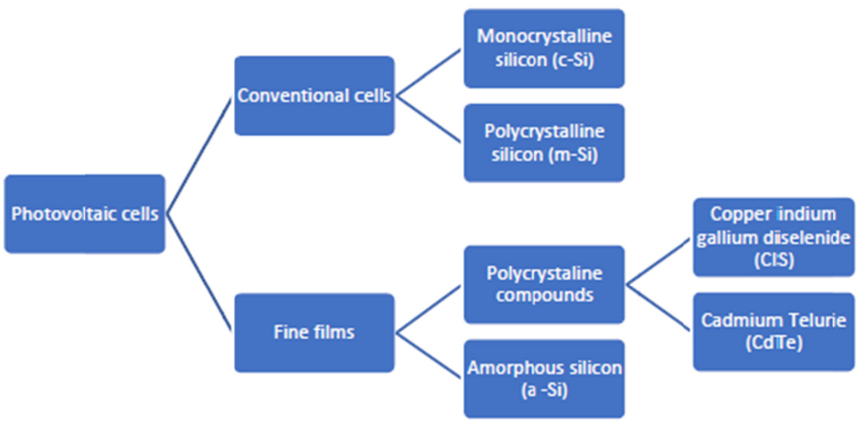

Figure 3. Commercial photovoltaic cell technologies

Source: BLUESOL, 2016.

The photovoltaic module consists of the electrical connection of photovoltaic cells in series or in parallel, in order to obtain the desired voltage and current values (Torres, 2012).

Figure presents several possible combinations for an association of 36 FV cells.

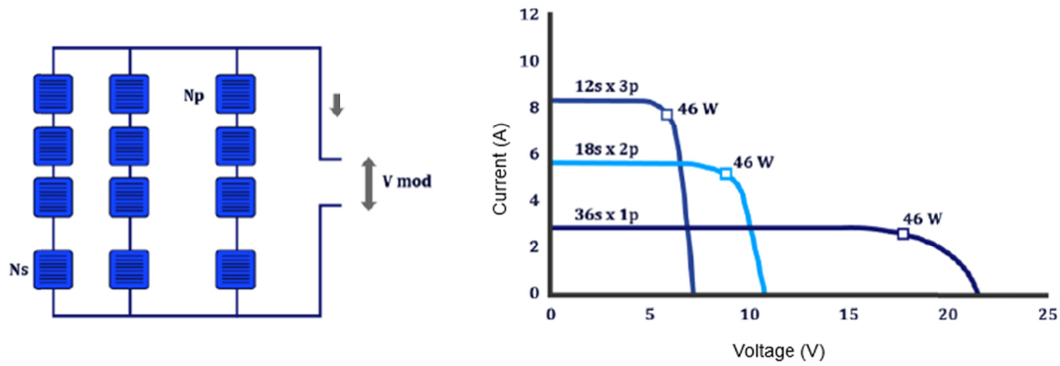

Figure 4. Scheme of series-parallel connection of several photovoltaic cells (left) and different I-V (current/voltage) curves obtained by the association of 36 photovoltaic cells (right)

Source: Onudi, 2016.

It can be observed (Figure 4) that, with the same number of cells, the power obtained is the same. What varies is the way to combine the pairs, allowing for the use of different voltages and currents, according to the project needs (Onudi, 2016).

Figure shows a Current/Voltage/Power chart of a photovoltaic cell.

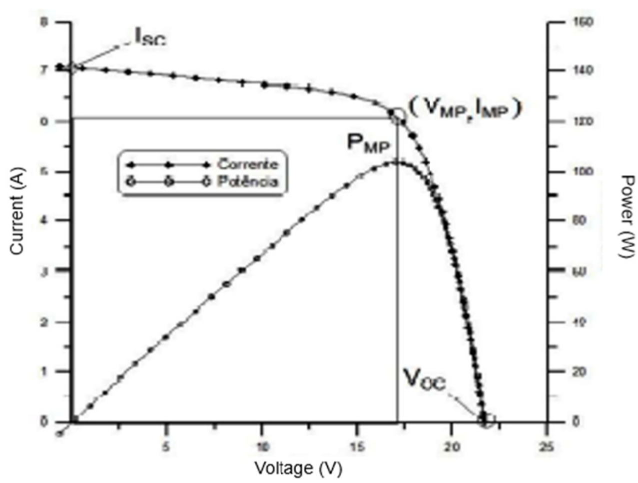

Figure 5. Current/Voltage/Power Chart of the MPPT (Maximum Power Point Tracker) concept

Source: CEPEL-CRESESB, 2014.

Figure 6 show the impact of increasing the solar irradiance and cell temperature on the I-V curve of photovoltaic, respectively.

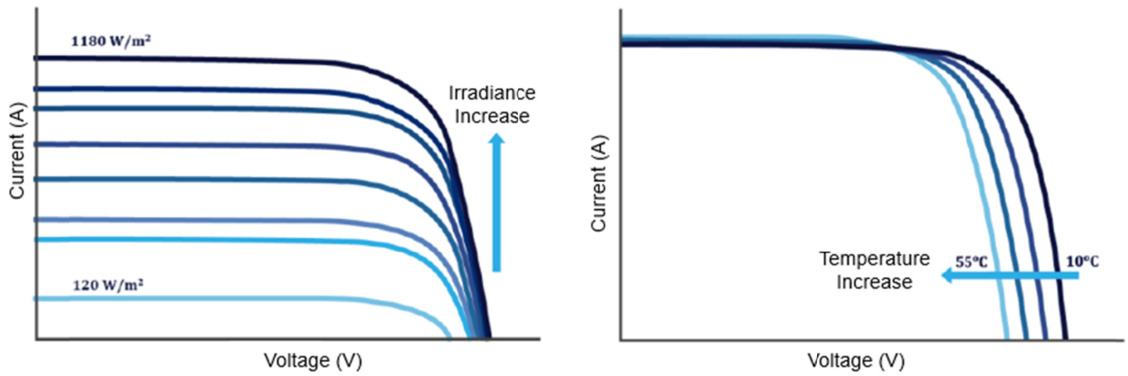

Figure 6. Influence of the variations of radiation and temperature on the characteristics of I-V (current/voltage) chart of a photovoltaic module

Source: Onudi, 2016.

The main factors that affect the I-V characteristics of the photovoltaic generator are photon intensity (solar radiation) and temperature. Solar radiation mainly affects the current, and temperature mainly affects the voltage.

3.2 Inverters

The inverter is an electronic device that converts DC (direct current) voltage into AC (alternating current) voltage. The inverters used in photovoltaic systems can be divided into two application categories, which are the specific inverters for grid-tied systems and the specific ones for applications in off-grid systems.

The functionality of both categories and operating principles is the same. The difference between the applications is that specific grid-tied system inverters have specific characteristics to synchronize and inject the energy into the concessionaire's grid (Filho, 2012).

In general, inverters intended for grid-tied and off-grid systems are required to meet certain characteristics so that they do not compromise the overall efficiency of the system. They are (BLUESOL, 2016):

- High conversion efficiency in both nominal and partial charges;
- High reliability and low maintenance requirements;
- Operation in a wide input voltage range;
- Good regulation of the output voltage;
- Sine waveform with low harmonic content;
- Low noise emission audible;
- Low emission of electromagnetic interference;
- Tolerance to startup surges in charges to be powered;
- Safety for people and the installation;
- Degree of protection (IP) appropriate to the type of installation.

3.3 Batteries

A battery is composed of a set of electrochemical cells connected in series and/or in parallel, which are capable of storing electrical energy in the form of chemical energy by means of a process of electrochemical oxidation and reduction that occurs in its interior (CEPEL-CRESBES, 2014).

When a charged battery is connected to an electrical charge, the reverse process occurs, *i.e.*, direct current is produced by the conversion of chemical energy into electrical energy.

In grid-tied systems, the use of battery banks is not necessary, as the energy consumed by the building is provided by the concessionaire's grid when solar radiation rates are low. In off-grid systems, the use of batteries is necessary so that, in periods of low solar radiation, the charge can be supplied without interruption. To do this, part of the energy generated by the photovoltaic panel is stored in batteries.

Of the various types of existing electrochemical accumulators, lead-acid batteries are still the most employed technology (BLUESOL, 2016).

Batteries with more modern technologies such as nickel cadmium (NiCd), nickel metal hydride (NiMH), and lithium ion (Li-ion), among others, despite presenting advantages (greater efficiency, longer service life, and greater discharge depth), are not yet economically feasible in most photovoltaic systems (Vera, 2004).

Among the specifications of a battery, the most frequently used for designing a photovoltaic system are charge rate, open circuit voltage, cut-off voltage, nominal voltage, discharge depth, and working temperature.

3.4 Charge controllers

The charge controller (or regulator) increases the efficiency of the photovoltaic system and the service life (number of cycles) of the batteries. A charge controller monitors the voltage of the batteries and protects them from undue overcharging.

The key functions of a charge controller are (BLUESOL, 2016):

- Control of the perfect recharge of the battery bank;
- Protection against unexpected overcharge;
- Protection against excessive discharge; and
- Provision of information on the battery bank level.

3.5 Protection Diodes

Under certain operating conditions, some or only one of the constituent modules of a photovoltaic panel may undergo shading. As a consequence of the shading, so-called hot spots appear (BLUESOL, 2016). If not diagnosed at the start of the project, these hot spots may permanently damage the entire module.

This happens because, when a cell runs out of solar radiation, it may compromise the entire line (because the cells are connected in series) and, instead of generating electricity, the line begins to behave as a charge.

When operating normally, the electrical energy generated by the photovoltaic cells is consumed by the charge that is connected to the module. When shading occurs—for example, due to a dry sheet covering the entire cell—it will be inversely polarized, behaving as a charge. All the energy received is converted into heat.

If the current passing through the cell is high enough, the hot spot will begin forming. The largest current that a cell can receive under these conditions is the short-circuit current (GREENPO, 2004).

To prevent hot spot formation, the current should be diverted from the cells through a bypass diode, which is connected to a set of cells with inverse polarization. Generally, the diodes are connected to groups of 18 or 20 cells, so that a 36-cell module has two diodes and a 72-cell module has 4 diodes (CEPEL-CRESESB, 2014).

4. Softwares Developed for the Sizing of Photovoltaic Systems

4.1 HOMER

Homer is the most widely used software for sizing and simulating renewable sources, available for download and free for trial purposes. It is suitable for quick pre-feasibility, optimization and sensitivity analysis in various possible configurations of renewable sources (Sinha & Chandel, 2014).

Homer allows data such as component costs, resource availability, manufactured data, etc., and simulates different configuration systems, generating results ordered by Net Present Value.

The major disadvantage of HOMER is that input variables should be inserted by the user or set as the limits of sensitivity analysis (Zahboune et al., 2016).

4.2 HYBRID 2

Hybrid 2 was developed by Renewable Energy Research Laboratories (RERL), from the University of Massachusetts, in the United States, with the support of the National Renewable Energy Laboratory (CEERE, 2016).

It allows for the simulation of systems consisting of up to three different generators, comprising wind turbines, photovoltaic modules, and diesel turbines.

Hybrid 2 uses a probabilistic model to explain the variations of energy generation in renewable systems, performing economic analysis and forecasting the performance of several hybrid systems (Sinha & Chandel, 2014).

A negative point of this software is the limited access to available parameters and the lack of flexibility. On the other hand, it presents a library with several resource data (Sinha & Chandel, 2014).

4.3 RETScreen

RETScreen is a feasibility study tool, comprising a free software program for download, developed by the Ministry of Natural Resources of Canada (RETScreen, 2013). The software simultaneously performs financial analysis and the analysis of environmental benefits of different renewable energy sources to anywhere in the world. Este software utiliza linguagem Visual Basic e C como plataforma de trabalho.

The software has a database of more than 6000 ground stations, which includes solar radiation indexes, power resource maps, etc.

The main limitations of RETScreen are to disconsider the effects of temperature for performance analysis of photovoltaic systems, to have no data import function, and to support no advanced calculations (Sinha & Chandel, 2014).

4.4 INSEL

The INSEL (Integrated Simulation Environment Language) general-purpose modeling language was developed by the University of Oldenburg, Germany, allowing users to build a structure with the aid of its library and user-specified execution time (INSEL, 2013).

This software has its own database of meteorological parameters from almost 2000 locations worldwide. For photovoltaic systems and thermal systems, data on solar radiation, temperature, humidity and wind speed can be generated using this software, based on the average values for a month, for any location and orientation.

This simulation software has the flexibility to generate configurations for the planning and monitoring of electrical and thermal energy systems.

4.5 TRNSYS

In 1975, the University of Wisconsin and the University of Colorado (United States) jointly developed a software program for energy system simulation called the Transient Energy Simulation Program (Trnsys) (Wisc, 2013).

Since its inception, Trnsys has undergone changes, currently including photovoltaic systems, solar concentration systems, and other forms of exploitation of thermal generation, which makes it a hybrid simulator.

Trnsys was initially developed for simulation of thermal systems, but it has now included photovoltaic systems, solar concentration systems, as well as other forms of utilization of thermal generation, making it a hybrid simulator.

Trnsys does not provide optimization options, but performs high-precision simulations with graphics and other details (Shandel, 2014).

5. Development of the FOTODIM Software

The purpose of the calculation tool developed is to size grid-tied and off-grid photovoltaic systems. The development of the computational tool was performed using the MATLAB software (Matrix Laboratory, Mathworks, Inc., version R2013a).

The sizing of photovoltaic systems depends, among other factors, on the climatological characteristics of the place or region where the project is to be carried out.

Grid-tied systems can be designed to meet the total demand of the building or a fraction thereof, as on days with low solar radiation, the chain of the local concessionaire supplies the consumption demanded by the building.

Off-grid systems can also be designed to meet the total demand of the building or a fraction thereof but require storage systems to supply power in periods with low solar radiation rates. Energy storage is usually performed using lead-acid batteries.

The software developed presents a database of equipment that can be used by users for the sizing of the photovoltaic system. The database also includes the average radiation of some municipalities of the State of Paraná, coming from the Brazilian Solarimetric Atlas (Tiba, 2000). The database allows the addition of new equipment and the registration of new locations.

The mathematical model used for photovoltaic design came from the Engineering Manual for Photovoltaic Systems (CEPEL-CRESESB, 2014), Photovoltaic Systems Technology, Design and Installation Manual (GREENPO, 2004), and the Solar System Introduction Digital Book (BLUESOL, 2016).

5.1 Survey of Available Solar Resources

The ideal tilt angle of the photovoltaic modules can be determined according to the latitude of the project site, the configuration of the photovoltaic system (grid-tied or off-grid) being a factor that affects the tilt angle calculation method. Thus, it is possible to calculate the tilt angle using only latitude data, using Equation 1 for off-grid systems and Equation 2 for grid-tied systems.

For off-grid systems, a higher tilt angle is recommended, as it ensures greater absorption of solar radiation in the periods close to the winter solstice, according to Equation 2 (BLUESOL, 2016).

$$\beta = \Phi + \frac{\Phi}{4} \quad (1)$$

Where, β: Panel tilt angle in relation to the horizontal plane (degrees); Φ: Latitude of the site or area (degrees).

For Grid-tie systems, smaller tilt angles provide greater absorption in the periods near the summer solstice, which increases the generation of energy in these periods. In this configuration, due to a potential financial benefit that occurs in tariff offsetting systems, as is the case in Brazil, the use of Equation 2 is suggested (BLUESOL, 2016).

$$\beta = 3.7 + 0.69 \cdot \Phi \quad (2)$$

In any of the photovoltaic systems (grid-tie or off-grid), it is recommended that tilt angles smaller than 10° are not affected, as the natural cleaning of the modules by atmospheric precipitation can be impaired (BLUESOL, 2016).

In the calculation tool developed, users have the possibility of changing the tilt angle of the modules and the azimuthal deviation of the modules. To correct the position of the modules, it is used Klein's methodology (Klein, 1977).

As energy production is directly related to solar radiation, the accumulated value of solar energy, over a one-day period, can be expressed using the number of Full Sun Hours (FSH), according to Equation 3 (CEPEL – CRESBES, 2014).

$$FSH = \frac{R_A}{1\left(\frac{kW}{m^2}\right)} \quad (3)$$

Where, FSH = Full Sun Hours (h/day); R_A = Average solar radiation (kWh m^{-2} day^{-1}).

This magnitude reflects the number of hours in which the solar radiation, throughout the day, is equivalent to a constant radiation and equal to 1 kW m^{-2}.

5.2 Grid-tied System Design

For the design of the grid-tied photovoltaic generator, the daily average consumption per year of the building (Wh day^{-1}) should be raised. This data can be calculated based on the history of monthly electricity bills issued by the local concessionaire.

5.2.1 Photovoltaic Panel

The power of the photovoltaic panel connected to the grid can be calculated by Equation 4 (CEPEL-CRESESB, 2014).

$$P_{VP} = \frac{E - \frac{E_{tf}}{TD}}{FSH_{AV}} \quad (4)$$

Where, P_{VP}: Peak power of the photovoltaic panel (Wp); E: Average annual daily consumption of the building (Wh day^{-1}); E_{tf}: Average annual daily consumption referring to the minimum consumption tariff charged by the concessionaire (cost of availability). For 3Ø systems, a monthly minimum value equivalent to 100 kWh $month^{-1}$ is charged, irrespective of the use. For two-phase systems with three (3) conductors, 50 kWh $month^{-1}$ is charged, and for single-phase or two-phase systems with two (2) conductors, 30 kWh $month^{-1}$ is charged; TD: performance rate (dimensionless); FSH_{AV}: annual average of the Full Sun Hours (FSH) incident on the photovoltaic panel plane (h day^{-1}).

5.2.2 Voltage Inverter

The inverter sizing factor represents the relation between the nominal power of the inverter and the peak power of the photovoltaic generator, as shown in Equation 5 (CEPEL-CRESESB, 2014).

$$ISF = \frac{P_{NAC}}{P_{VP}} \quad (5)$$

Where, ISF: Inverter sizing factor (dimensionless); P_{NAC}: nominal power of the inverter, in AC (W).

The power of both the photovoltaic panel and the inverter must be adjusted so that the inverter's ISF has the best cost/benefit ratio. The ISF depends on the selected inverter, photovoltaic module technology, orientation and tilt angle of the panel, and environmental conditions such as temperature and local radiation.

(1) Inverter Input Voltage

The input voltage of the inverter is the sum of the voltages of the photovoltaic modules associated in series. Because the voltage is strongly dependent on temperature, the extreme conditions of winter and summer should be used in the design.

The maximum system voltage occurs when the photovoltaic panel is still in open circuit (V_{OC}) at low temperatures. This can happen during the winter period, even at sunrise, when the system voltage rises based on the low temperature of the photovoltaic panel, and the inverter has not yet connected to the grid due to the low radiation.

During the summer, the temperature of the photovoltaic modules in Brazil can reach values higher than 70°C, resulting in a reduction of the system voltage, due to the negative temperature coefficient. It is thus necessary to assess whether the PV panel has a sufficient number of modules connected in series so that the panel voltage is higher than the minimum voltage of the MPPT (Maximum Power Point Tracker) system of the inverter. If the panel voltage drops below the minimum MPPT voltage of the inverter, its efficiency will be compromised and may cause its disconnection.

Based on these considerations, the number of modules connected in series can be calculated through Equation 6 (CEPEL-CRESESB, 2014).

$$\frac{Vi_{MPPTmin}}{V_{mpTmax}} < \text{No. of modules in series} < \frac{Vi_{MPPTmax}}{V_{mpTmin}} \qquad (6)$$

Where, $Vi_{MPPTmin}$: Minimum operating voltage of the input MPPT of the inverter (V); $Vi_{MPPTmax}$: Maximum operating voltage of the input MPPT of the inverter (V); V_{mpTmin}: maximum power voltage (V_{mp}) of a photovoltaic module at the lowest expected operating temperature (V); V_{mpTmax}: maximum power voltage (V_{mp}) of a photovoltaic module at the highest intended operating temperature (V).

(2) Inverter Input Current

The inverter has a maximum continuous input current. To ensure that this value is not exceeded, it is possible to calculate the maximum number of photovoltaic modules connected in parallel using Equation 7 (CEPEL-CRESESB, 2014).

$$\text{No. of modules in parallel} = Ii_{max}/I_{sc} \qquad (7)$$

Where, Ii_{max}: Maximum input current input to the inverter; I_{sc}: Short-circuit current of the photovoltaic module at the expected temperature.

5.3 Sizing of Off-Grid Systems

Off-grid systems were designed according to the critical month method, considering that, based on an energy balance carried out during the year, the critical month is the one with the least favorable average conditions for the system (lower solar radiation with greater use of charges). It is assumed that, if the system works properly during said month, the same will happen for the other months of the year. Therefore, the system will produce more energy than necessary in other months, during which average conditions will be more favorable.

5.3.1 Electricity Demand and Consumption

To start the sizing of an off-grid system, it is necessary to know the demand and the consumption that the PV system will need to meet. The power, quantity and time of use of the equipment must be defined.

The most traditional way to determine the energy consumption of a consumer unit is to add the energy consumed of each device throughout the day (Wh day^{-1}). To do this, the user is offered a list of devices with their respective powers, coming from PROCEL (National Electricity Conservation Program). The user can add other equipment to the list or change the existing ones. If the user already has the power demand of the building (kW), based on any other calculation methodologies, this value can be fed directly into the software.

5.3.2 Voltage Inverter

After defining the list of devices that will be part of the building, as well as their maximum power demand (kW), it is possible to size the inverter to be used.

For charges requiring peak power, such as induction motors during startup, it is necessary to be aware of this power, along with its duration, in order to define the surge capacity that the inverter is able to withstand.

The user should set the operating voltage of the system (12, 24, 36 or 48 V_{DC}), and the rated inverter should have the same input voltage as the system voltage and the output voltage (V_{AC}), according to the requirements of the charges to be reached, usually 127 V_{AC} or 220 V_{AC}, 60 Hz.

5.3.3 Battery Bank

The total daily energy consumed by the building is initially calculated, using equation 8 (CEPEL-CRESESB, 2014).

$$L = \frac{L_{DC}}{\eta_{bat}} + \frac{L_{AC}}{\eta_{bat} \cdot \eta_{inv}} \tag{8}$$

Where, L: Total daily energy consumed by the building in a given month (Wh day^{-1}); L_{DC}: Energy consumed daily in DC in a given month (Wh day^{-1}); L_{AC}: Energy consumed daily in AC in a given month (Wh day^{-1}); η_{bat}: Overall battery efficiency (decimal); η_{inv}: Inverter efficiency (decimal).

The capacity of the battery bank is calculated by Equation 9 (CEPEL-CRESESB, 2014).

$$CB_{C20}(wh) = \frac{L \cdot N}{dd} \tag{9}$$

Where, CB_{C20}: The capacity of the battery bank in Wh for the discharge regime in 20 hours (Wh); N: Number of days of autonomy, typically between 2 and 4 (days); dd: Battery discharge depth (decimal); The number of days of autonomy is the period that the battery bank will meet the independent building of photovoltaic generation. This happens on days of high cloudiness and low rates of solar radiation.

The capacity of the battery, in Ah, is given by Equation 10 (CEPEL-CRESESB, 2014).

$$CBI_{C20}(Ah) = \frac{CB_{C20}}{V_{syst}} \tag{10}$$

Where, CBI_{C20}: Battery capacity (Ah); V_{syst}: System working voltage (V).

The number of batteries in parallel is calculated by Equation 11 (CEPEL-CRESESB, 2014).

$$\text{No. batteries in parallel} = \frac{CBI_{C20}}{CBI_{bat}} \tag{11}$$

Where, CBI_{bat}: Capacity of the selected battery (Ah).

The number of batteries connected in series depends on the nominal voltage of the system and is obtained by Equation 12 (CEPEL-CRESESB, 2014).

$$\text{No. batteries in series} = \frac{V_{syst}}{V_{bat}} \tag{12}$$

Where, V_{bat}: Nominal voltage of the battery (V).

5.3.4 Photovoltaic Panel

The power required for the photovoltaic panel is obtained by Equation 13 (CEPEL-CRESESB, 2014).

$$P_m = \frac{L}{FSH \cdot Red_1 \cdot Red_2} \tag{13}$$

Where, Red_1: Reduction factor of the power of the photovoltaic modules, in relation to their nominal value, encompassing the effects of: i) a possible accumulation of dirt on the surface over the time of use; ii) permanent physical degradation; iii) manufacturing tolerance for less than the nominal value; iv) losses due to temperature. Red_1 is assigned a default value of 0.75 (decimal) for c-Si photovoltaic modules; Red_2: Power reduction factor due to system losses, including wiring, controller, diodes etc. At this value, the value of 0.9 (decimal) is recommended as default.

The determination of the number of modules in series (Equation 14) should consider the system voltage and the maximum power of the modules when operating at the highest temperature for the project site (V_{mpTmax}).

$$\text{No. modules PV in series} = 1.2 \cdot \frac{V_{syst}}{V_{mpTmax}} \tag{14}$$

Where, V_{mpTmax}: Maximum power voltage for the highest expected temperature for the site where the modules are to be installed (V).

The maximum power voltage at the highest (or lowest) predicted temperature is calculated by Equation 15 (CEPEL-CRESESB, 2014).

$$V_{mpTmax}\left(\text{or } V_{mpTmin}\right) = V_{mp} \cdot \left[1 + \gamma \cdot \left(T - 25\right)\right] \quad (15)$$

Where, V_{mp}: Maximum power voltage of the photovoltaic module (V); T: Maximum or minimum working temperature for the photovoltaic module (°C); γ: Coefficient that relates the variation of the voltage produced in relation to the panel temperature (°C^{-1}).

The current generated by the photovoltaic panel is presented in Equation 16 (CEPEL-CRESESB, 2014).

$$I_m = \frac{P_m}{V_{syst}} \quad (16)$$

Where, I_m: Photovoltaic panel current (A).

The number of photovoltaic modules to be connected in parallel is given by Equation 17 (CEPEL-CRESESB, 2014).

$$\text{No. modules in parallel} = \frac{I_m}{I_{sc} \times 1.25} \quad (17)$$

Where:

I_{sc}: short-circuit current of the photovoltaic module (A).

A safety factor of 25% is added to the short-circuit current of the photovoltaic module, assuming that the module can receive a radiation up to 1,250 W.m^{-2} (even for short periods).

5.3.5 Charge Controller

The required number of controllers in parallel is presented in Equation 18 (CEPEL-CRESESB, 2014).

$$\text{No. controllers in parallel} = \frac{I_m}{I_{ctl}} \quad (18)$$

Where, I_{ctl}: maximum input current of the controller (A).

5.4 Economic Analysis

For the evaluation of the economic feasibility of the photovoltaic system deployment, three indices are used: Net Present Value, Internal Rate of Return, and Discounted Payback (Casarotto and Kopittke, 1998). To obtain these indices, the costs of implementing the photovoltaic system are compared to the costs of conventional electricity supplied by the local concessionaire.

6. Software Presentation

The developed application was designated as "FOTODIM," allowing users to provide a versatile and intuitive calculation tool, with the interaction of technical sizing and economic analysis, based on equipment found in the Brazilian market. Figure 7 illustrates the FOTODIM home screen.

Figure 7. FOTODIM home screen

The start screen of FOTODIM aims to present the tool. The “Ajuda” (Help) menu informs the user of the purpose of the application. The “Iniciar” (Start) button directs the user to the Setup screen.

Figure 8 shows the Configuration Selection screen, showing the image of grid-connected photovoltaic systems.

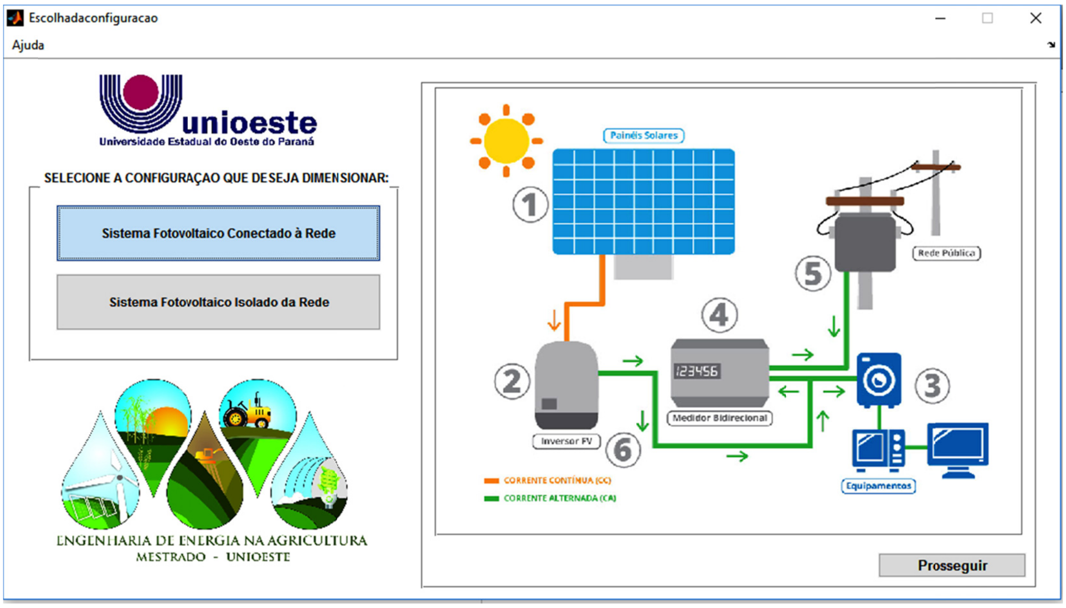

Figure 8. Setup screen showing the image of a photovoltaic system connected to the grid

Figure 9 shows the Setup screen, showing the image of off-grid photovoltaic systems.

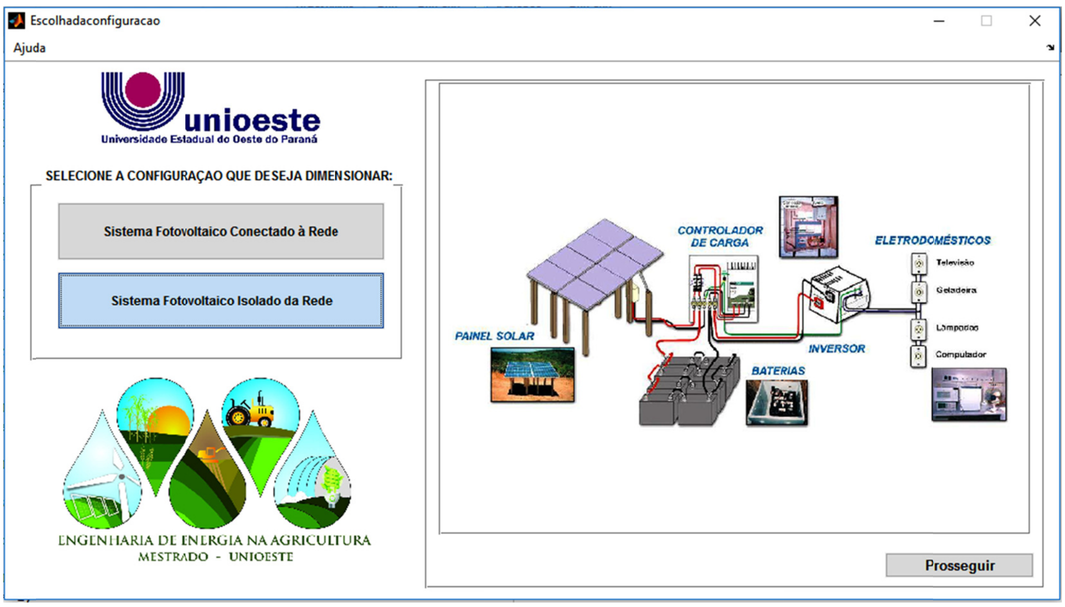

Figure 9. Setup screen showing the image of an off-grid photovoltaic system

After the photovoltaic system is defined, the tool proceeds to the data entry step. For the grid-tied system, the user informs the history of the consumption of the building, while for the off-grid system, the user enters the details of the consumption and demand of the equipment that will be part of the system.

6.1 Grid-tied Photovoltaic System

In this step, the user enters the history of consumption of the building to be serviced by the photovoltaic system (Figure 0).

Figure 10. Input data of consumption and voltage data contracted for the building

In the next step, the user defines the city where the project is to be carried out and the orientation of the modules. The software will present the graphs for horizontal solar radiation, ambient temperature, and corrected solar radiation due to the orientation of the modules (Figure 1).

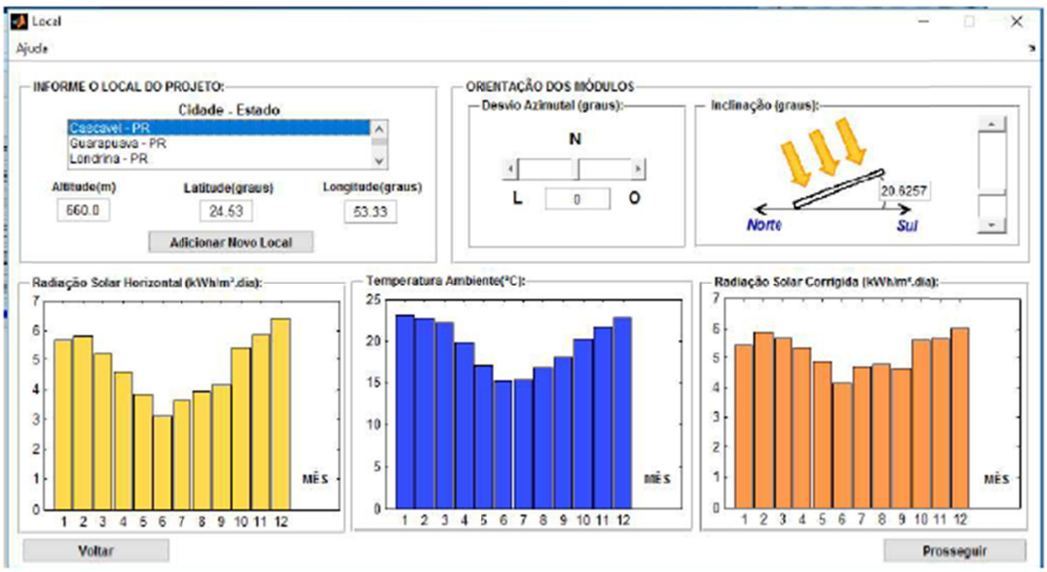

Figure 11. Screen for selecting the project location and orientation of the modules

If the application fails to display the city the user desires, the user can enter the city of their choice, along with the solar radiation and ambient temperature data using the “Adicionar Novo Local” (Add New Location) button.

The following step concerns the choice of inverters and photovoltaic modules (Figure 12).

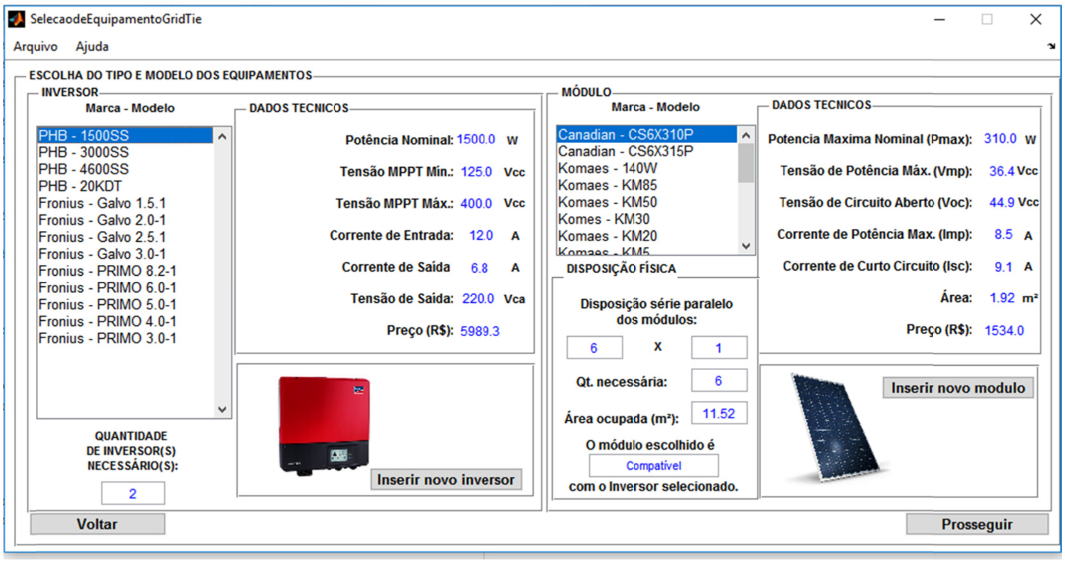

Figure 12. Screen for selecting inverters and photovoltaic modules

The equipment list presents all equipment models in the FOTODIM database. The software automatically evaluates the compatibility between the chosen equipment sets.

The next step is related to equipment sizing and economic evaluation (Figure 13).

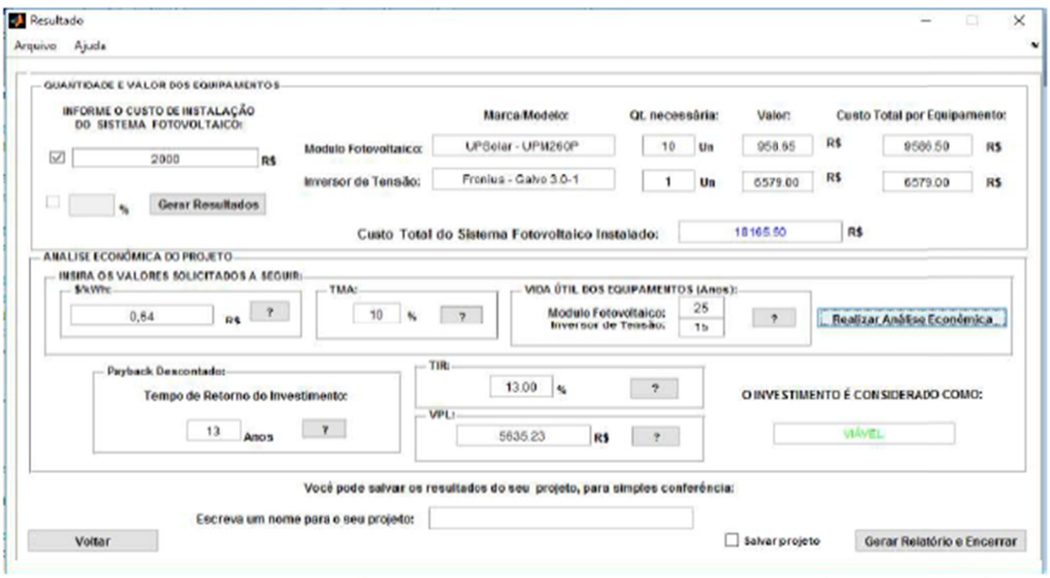

Figure 13. Screen for equipment sizing and economic evaluation

The user enters the installation costs of the photovoltaic system, as well as the service life of the equipment, minimum rate of attractiveness (MRA), and electricity tariff charged by the concessionaire. Based on these data, the software calculates some economic feasibility indices of the project (Net Present Value, Internal Rate of Return, and Discounted Payback), and presents all equipment sized, with the respective quantities and configurations. If the Net Present Value is greater than zero, the Internal Rate of Return is greater than the Minimum Rate of Attractiveness (MRA), and the Discounted Payback is less than the service life of the investment, the software considers the investment to be economically feasible.

In this screen, users can also generate a project report in which all project entry data are presented, as well as the results of the sizing and economic evaluation carried out. The report also presents a chart comparing the energy consumption of the building with the energy generation carried out by the photovoltaic panel sized.

6.2 Off-grid Photovoltaic System

In this configuration, the user is required to enter the equipment and the usage regime of each equipment set, in hours per day and in days per month. For each saved device, FOTODIM calculates consumption and total demand and presents it to the user. Figure14 presents the demand data and equipment consumption screen. The software allows all equipment sets in the database to be edited, as well as the addition of new equipment.

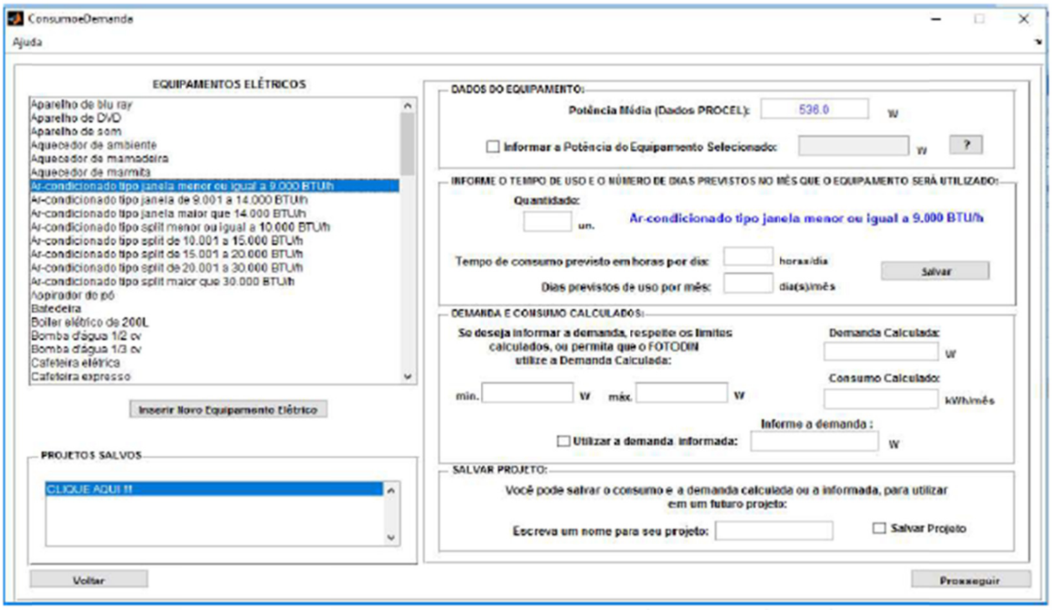

Figure 14. Electrical equipment consumption and demand screen

The next step will be the choice of the city where the project is to be carried out, as well as the orientation of the modules. This phase is similar to the one presented in the previous item.

The next step is related to the choice of equipment. The first equipment set to be chosen comprises the voltage inverters and the batteries (Figure15).

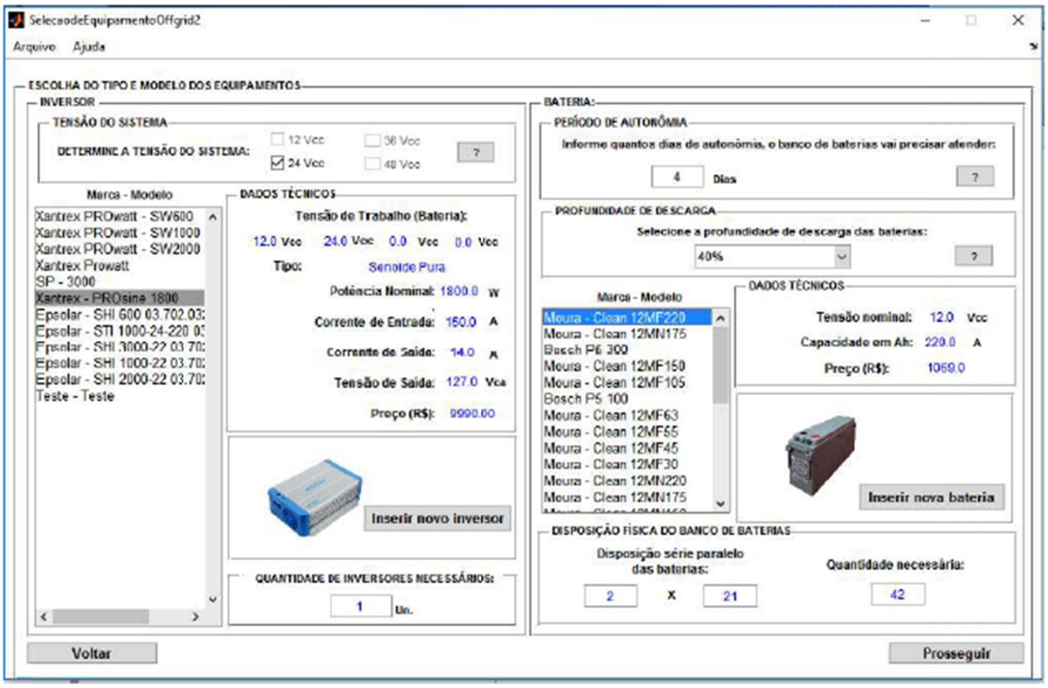

Figure 15. Screen for selection of voltage inverters and batteries

FOTODIM calculates the quantity required for the project for each selected inverter model and checks if the inverter has voltage compatible with the rest of the system. For batteries, similarly, the software calculates the quantity and serial-parallel arrangement thereof.

The next step is the selection of the charge controller model and photovoltaic module (Figure 16).

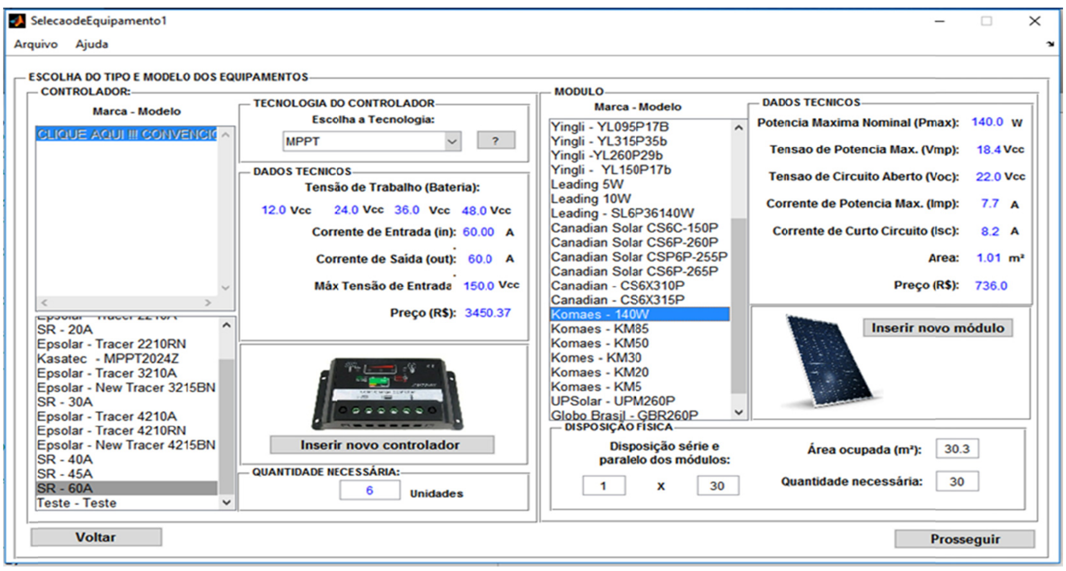

Figure 16. Screen for selection of charge controllers and photovoltaic modules

To choose the model charge controller, the user should first define the controller technology to be used in the project: PWM (Pulse Width Modulation) or conventional and MPPT (Maximum Power Point Tracker). Once the controller technology is defined, the software calculates, for each selected model, the quantity of controllers required to support the electrical current of the system. Additionally, the software checks the compatibility of the controller's working voltage with the rest of the system.

With regard to photovoltaic modules, for each selected model, the application calculates the quantity, occupied area and the series-parallel arrangement thereof, as well as checking the compatibility with the other selected equipment.

The last stage of the project is the execution of the economic analysis and presentation of the sizing results of the system, containing all the equipment that will be used (Figure17).

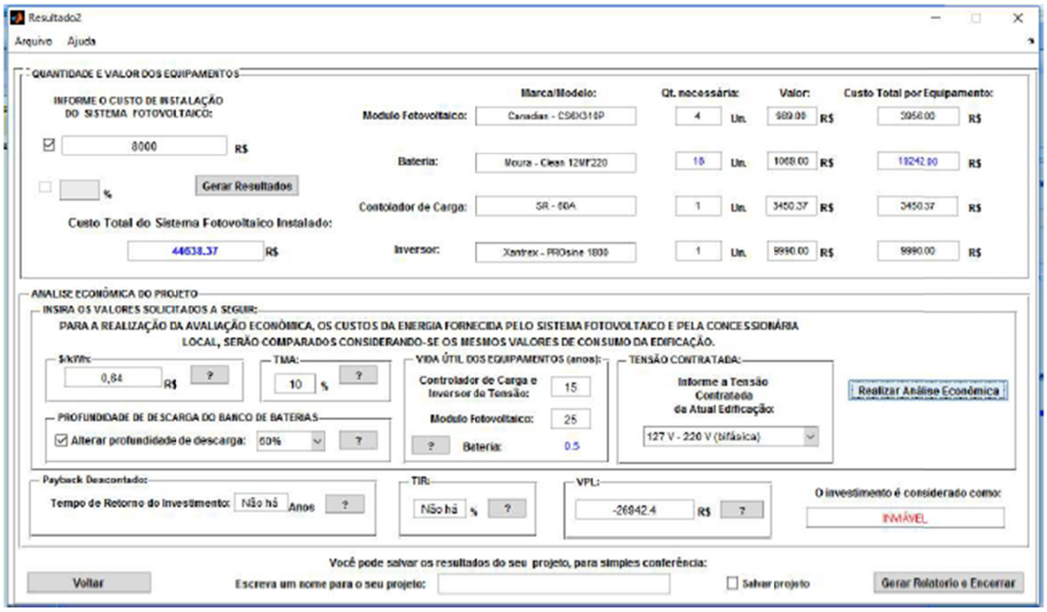

Figure 17. Screen for equipment sizing and economic evaluation

6.3 Example of Sizing a Grid-Tied System Using FOTODIM

The following is an example of a grid-tied photovoltaic system designed by FOTODIM. Tables 2 to 7 present the sizing data and results.

Table 1. History of monthly consumption reported

Consumption History of the Building (kWh/month)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
303	332	283	239	307	193	199	226	217	263	245	261

Table 2. Characteristics of the project site selected

Project site	**Altitude**	**Longitude**	**Latitude**	**Azimuthal Deviation**	**Tilt Angle**	**Panel Power**
Cascavel, PR	660.0 m	53.33°	24.53°	0°	20,6257°	1550 Wp

Table 3. Horizontal solar radiation incident at the project site

Horizontal Solar Radiation (kWh/m² day)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5.67	5.83	5.25	4.58	3.81	3.11	3.61	3.92	4.14	5.44	5.86	6.39

Table 4. Solar radiation for grid-tied systems

Corrected Solar Radiation (kWh/m² day)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5.42	5.87	5.66	5.37	4.84	4.12	4.69	4.75	4.6	5.6	5.67	6.02

Table 5. Selected photovoltaic equipment for grid-tied systems

Equipment	Brand-Model	Quantity	Value	Total	Useful life
Photovoltaic Module	Canadian-CS6X310P	5	R$989.00	R$4,945.00	25 years
Voltage Inverter	Fronius-Galvo 1.5.1	1	R$3,899.00	R$3,899.00	15 years

Table 6. Economic analysis results for grid-tied systems

Installation	Investment	MRA (%)	IRR (%)	NPV (R$)	Payback	Investment Useful Life
R$2,000.00	R$10,844.00	10	13.2	2,608.81	13 years	25 years

The graph shown in Figure **1**18 is available in the report generated by the software. The blue color bar represents the energy consumed, and the red color bar represents the generation of the photovoltaic panel, both in kWh/month. The y-axis represents the values of energy consumed (kWh month^{-1}), and the x-axis represents the months of the year.

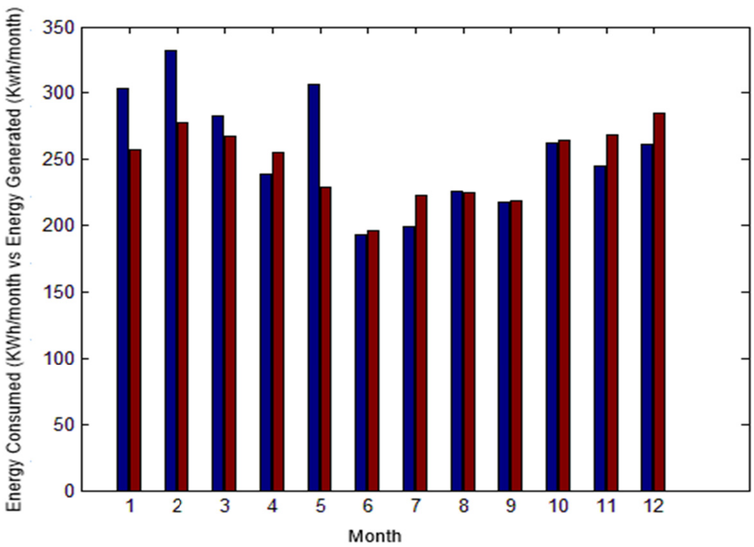

Figure 18. Consumption vs. power generation of the proposed project for grid-tied photovoltaic systems

The graph shown in Figure 19, also available in the report, represents the discounted cash flow accumulated over the project's 25-year life. It can be verified that the discounted payback occurs in the 12th year. The y-axis is represented in R$, and the x-axis is represented in years.

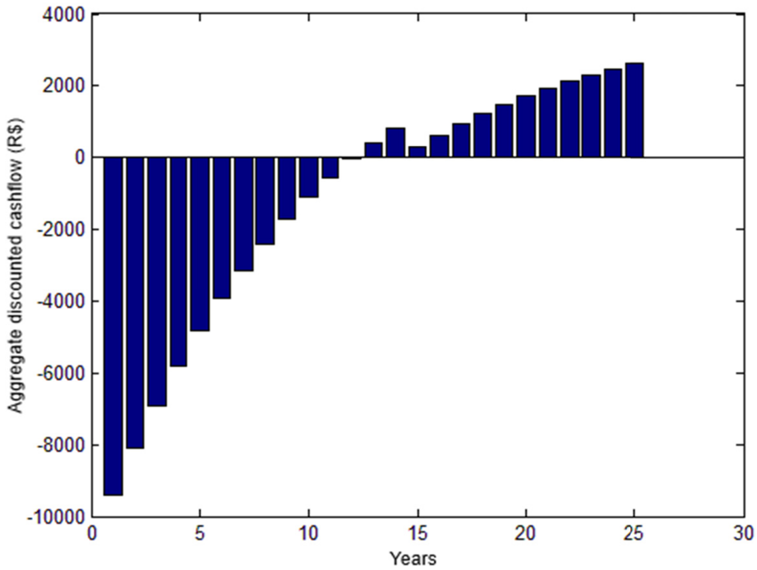

Figure 19. Chart of the time of the investment return for grid-tied photovoltaic systems

The results show that FOTODIM software allows to determine all the costs of the photovoltaic system. Similarly, Al-Karaghouli and Kazmerski (2010) used HOMER software to scale a photovoltaic solar system to a health clinic located in a rural area in southern Iraq. The authors obtained a system consisting of 6 kW of photovoltaic modules, 80 batteries and an inverter of 3 kW. The initial cost and total cost of energy produced for this system were, respectively, US $ 50,700 and US $ 0.238/kWh.

7. Conclusions

The calculation algorithm for grid-tied and off-grid photovoltaic systems for the Brazilian market was defined using research in books and technical manuals related to solar energy and market research. The software proved to be a versatile calculation tool, allowing users to obtain the sizing without the data being lost, in a reliable manner, as the entire sizing algorithm and economic analysis calculations have a theoretical basis.

FOTODIM presents a very flexible database, in which all the equipment can be edited, and new equipment can be added. The result of the economic analysis clearly shows the economic feasibility indices of the project, which are calculated based on all costs and revenues of the system, equipment service life, and interest rate considered. The final report generated by FOTODIM provides all the information and results of the sized project, allowing users to perform a number of simulations with the equipment available on the domestic market.

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