Energetic and Environmental Benefits of Residential Solar Microgeneration Added to Electric Vehicle Recharging in the City of Rio de Janeiro

Paulo Eduardo Darski Rocha, Fernando Jorge Monteiro Dias, Sergio Escalante, and Luiz Arthur Pecorelli Peres

***Abstract*—This work investigates the performance of residential microgeneration photovoltaic PV systems connected to the electrical grid. It considers the overall available energy for powering households and charging electric vehicles (EVs). The conducted assessments elucidate the developed methodology and criteria for sizing PV panels, utilizing calculations derived from PV-SOL software. Analysis of atmospheric emissions indicates a reduction in greenhouse gases, notably fossil carbon dioxide (CO_2). These assessments have been compared to internal combustion vehicle (ICV) calculations, expressed in the annual equivalent number of trees required to neutralize emissions. Results from Rio de Janeiro, with ample annual sunlight availability, show a positive energy supply balance for such installations. Combining PV power with EV charging is promising, assuming an average daily journey of 84 km and nighttime charging occurring approximately 4 hours after peak hours.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/8949

***Index Terms*—photovoltaic generation system, electric vehicles, carbon neutralization.**

I. Introduction

In recent years, there has been a substantial increase in the use of PV cells to capture solar radiation and generate electricity as a renewable energy source [1]–[3]. Due to Rio de Janeiro's geographical location in Brazil, which is characterized by high levels of solar radiation, the use of PV systems is much more advantageous [4] compared to cities in the northern hemisphere where sun exposure levels are lower. Furthermore, the high electricity tariffs in Brazil, along with decreasing equipment costs and improving PV module efficiency, have sparked a growing interest in utilizing these sources. Currently, there have been favorable technological advancements in the manufacturing of solar panels, with improvements in efficiency and technology. PV module manufacturers have been working hard to develop more flexible and adaptable equipment, particularly integrated into building constructions for both residential and commercial purposes. Solar panels not only generate electricity but also provide additional functionalities in buildings and residences, such as weather protection, thermal insulation, partial shading, and even serving as a replacement for traditional roofing tiles [5].

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A. Regulatory Aspects of Microgeneration in Brazil

Through Normative Resolution No. 1.059/2023 [6], the Brazilian Electricity Regulatory Agency (ANEEL) [7] provides for the connection of consumer units with mini or microgeneration systems to the power distribution and their adherence to the power compensation system, known as "net metering". Microgeneration units are those with an installed capacity equal to or less than 75 kW [7]. Most consumers with a secondary power supply and a PV system are classified as microgenerators. They can supply active electrical power to the grid.

In the "Brazilian net metering" system, when the electricity supplied to the grid exceeds the energy consumed by the individual consumer, the micro producer has 60 months to use the excess power credits, referred to as a "bonus". The surplus is calculated as the variance between the energy that is injected and the energy that is absorbed.

The requirements for a cost related to the availability of an electrical system, which applies to the minimum monthly revenue of residential units, are established by ANEEL's Normative Resolution 414/2010. The cost is determined as the equivalent of 30 kWh for single-phase consumers, 50 kWh for two-phase consumers, and 100 kWh for three-phase consumers, based on the current currency value. As a result, the PV system can be appropriately designed based on the average monthly consumption (kWh) minus the corresponding energy cost at the supply category availability (kWh).

EV technology has been around for over a century but has faced challenges such as limited battery life and the rapid advancement of ICV technology. However, recent advancements in energy storage, particularly in batteries, have overcome these limitations. Moreover, EVs offer significant environmental benefits by reducing CO_2 emissions compared to ICVs. Another advantage of EVs is the existing inverter/converter technology, which enables their integration into intelligent electrical systems. This technology allows EV batteries to be used to supply power to the owner's consumption unit for an extended period. In other words, electric vehicle (EV) batteries can intelligently store energy to meet the electrical power demands of the owner's household, providing a sustainable and efficient energy solution [8], [9]. In Brazil, EVs are slowly gaining popularity, with government incentives aimed at boosting production and purchases. However, challenges in charging infrastructure persist. While major cities like São Paulo and Rio de Janeiro are making progress, hurdles remain. Despite this, the EV market is expanding, with automakers introducing more models. Brazil's natural resources and environmental awareness highlight the potential of EVs in reducing emissions. The high cost of EVs and the lifetime of the batteries remain barriers, but ongoing advancements and government support are expected to drive broader adoption.

The urban distribution system components, including transformers and low to medium-voltage distribution cables, are designed to accommodate future demand throughout their entire lifetime. This involves accounting for the rise in demand due to the increased use of EVs charging [4]. In areas undergoing development, the gradual increase in demand, stemming from the installation of charging stations and new equipment, allows distributors to plan for future upgrades and reinforcements in the electrical network [10]. Due to the significantly lower cost per mile traveled by EVs compared to internal ICVs in Brazil, the installation of EV charging systems in units combined with PV microgenerators has become an appealing option for users. This is especially true when the average daily distance traveled allows for a return on investment (ROI). Interestingly, the charging process for multiple EVs is stochastic, with a low risk of overloading distribution transformers connected to residential units [11].

According to ANEEL, the White Time of Use-Seasonal Tariff (THS) – Group B (Low Voltage) modality can be adopted for measuring residential units in Brazil. In this context, the White tariff consists of different values for energy consumption, depending on the specific time of day when the consumption occurs. This tariff is specifically available for low-voltage units, such as individual households or small businesses. The White Tariff is advantageous for owners or users of EVs, because nighttime charging (during dawn) is common, resulting in significant cost savings during the charging process due to the much greater energy efficiency of EVs compared to ICVs. The White Tariff allows for reduced nighttime kWh costs, below standard consumption tariffs, and provides free meter exchanges. Also, the use of renewable energy and electric vehicles significantly reduces carbon dioxide CO_2 emissions [12], [13].

The energetic and environmental benefits of integrating PV technologies with driving EVs in Rio de Janeiro are promising and significant. This approach helps to reduce fuel-derived CO_2 emissions, creating opportunities for new public power initiatives to further support and enhance these technologies [14]. According to the most recent National Energy Balance report, the transportation sector in Brazil accounts for approximately 30% of the country's total energy consumption. Notably, 93% of this consumption is allocated for use on roadways. However, Brazil has one of the most sustainable energy matrices in the world, but its transportation sector only accounts for 0.4% of electricity consumption.

The data provided forms the basis for the transition to electric-powered road transportation. This study aims to investigate the implementation of a typical residential photovoltaic PV microgeneration system that is connected to a distribution network in the city of Rio de Janeiro. The PV-SOL software was used for this purpose [15], [16]. The system sizing is based on availability costs and average monthly consumption of households that use conventional appliances, EVs, and recharging stations connected to the distribution board. In a bottom-up approach, the environmental impact assessment considers the reductions in fossil CO_2 emissions from battery EVs and PV microgeneration. These avoided CO_2 emissions from fossil fuels are quantified as the equivalent reforestation that would be necessary in the absence of PV microgeneration and EVs. The portion of the distribution network that is sourced from thermal electrical power emissions is considered a credit for avoided emissions from EV.

B. *Energy Matrix in Brazil*

This section provides a bottom-up environmental analysis, considering avoided fossil CO_2 emissions according to a PV and EV combination, replacing ICV and factoring in fossil fuel-based polluting energy sources coupled to the electrical grid. Even though this work focuses on the introduction of EVs in Rio de Janeiro, it is relevant to mention data from the energy and transportation matrix in Brazil. There are expressive technical arguments to promote sustainable development in Brazil. Following [17] the contribution of renewable energy sources in the Brazilian mix remains among the highest in the world, at approximately 48,4%. Higher percentages of sugarcane biomass, hydroelectricity, firewood, charcoal, and other sources like wind and solar, all contribute to this percentage. Table I presents the domestic energy supply breakdown.

TABLE I
ENERGY SUPPLY IN BRAZIL

Renewables	(%)
Sugar cane biomass	17
Hydraulic	12
Firewood and charcoal	8
Others (black liquor, wind, solar)	5,9
Non-Renewables	(%)
Petrol and oil Products	36,4
Natural Gas	13
Coal	5,7
Uranium	1,4
Other non-Renewables	0,6

Table II presents the energy usage across the entire country, detailing the final energy consumption per sector.

However, as indicated in Table II, the energy consumption in the transport sector comprises nearly one-third of the total. This sector shows a high amount of non-sustainable energy usage, around 80% (including diesel oil, gasoline, aviation kerosene, and natural gas), as shown in Table III.

Since the 1970s, energy consumption in the road transport sector has consistently increased, as mentioned in [18]. The penetration of EVs in the transportation system will reduce energy consumption and CO_2 emissions in the coming years.

TABLE II
FINAL ENERGY CONSUMPTION PER SECTOR

Sector	(%)
Industry	33
Transport	33
Households	9,7
Energy sector	10
Agriculture and livestock	4
Services	4,8
Non-energy uses	5,8

TABLE III
TRANSPORT SECTOR ENERGY CONSUMPTION

Energy Type	%
Diesel Oil	44
Gasoline	29
Ethanol	16
Aviation Kerosene	3,9
Biodiesel	3,3
Natural gas	2,1
Others	0,9

Power systems have become more efficient, as shown in international analyses [19].

In Brazil, 85% of electricity production comes from renewable sources, with 0,4% of this energy being used in the transport sector. There is a significant connection between the Brazilian transportation system, which is highly reliant on ICVs, and its environmental impacts. The data presented are based on the latest National Inventory of Atmospheric Emissions from Road Motor Vehicles, which was published by Brazilian government agencies in 2017 [17]. This inventory considers the widespread adoption of flex fuel, ethanol, and gasoline in the automotive fleet since 2003.

The Air Pollution Control Program by Motor Vehicles (PROCONVE / PROMOT) was created on May 6, 1986, by resolution 18 of the National Council for the Environment (CONAMA), coordinated by Brazilian Institute of Environment and Natural Resources Renewables (IBAMA), established and updated the emission limits for vehicles in collaboration with National Air Quality Control Program (PRONAR). Both PROCONVE and PROMOT work helped to reduce road vehicle atmospheric emissions. By this inventory, the road vehicle fleet is composed of 57% of automobiles, 28% of motorcycles, 11% of light commercial vehicles, 3% of trucks, and 1% of buses. The Automobiles are responsible for 47% of carbon monoxide CO, 7% of nitrogen oxides NOX, 14% of particulate PM material, 11% of aldehydes RCHO, 47% of non-methane hydrocarbons NMHC, 55% of nitrous oxide N_2O. In addition, automobiles are also responsible for 47% of methane CH_4 mainly because of urban taxi fleets equipped with compressed natural gas (CNG). The automotive industry is responsible for 33% of carbon dioxide emissions, highlighting the importance of transitioning to EVs and using renewable energy sources, such as solar power. This aligns with the Sustainable Development Goals of the 2030 agenda.

The objective of this work is to evaluate the performance of residential microgeneration photovoltaic systems connected to the grid, with a focus on supplying power to households and charging electric vehicles. This involves developing a theoretical model to predict monthly energy generation and comparing it with PV-SOL software predictions, as well as assessing the reduction of greenhouse gas emissions, particularly fossil carbon dioxide emissions, facilitated by photovoltaic microgeneration and electric vehicles. These assessments of atmospheric emissions aim to demonstrate the potential reduction in greenhouse gases achievable through these technologies, comparing emissions with those of internal combustion vehicles and expressing them in terms of equivalent trees. This analysis enables evaluation of the equivalent number of adult trees needed to offset these emissions when compared to the methodology purpose of this work.

II. METHODOLOGY

For the study's development, it was adopted the process presented in the flowchart of Fig. 1. The following sections detail the stages of consolidating the proposed methodology.

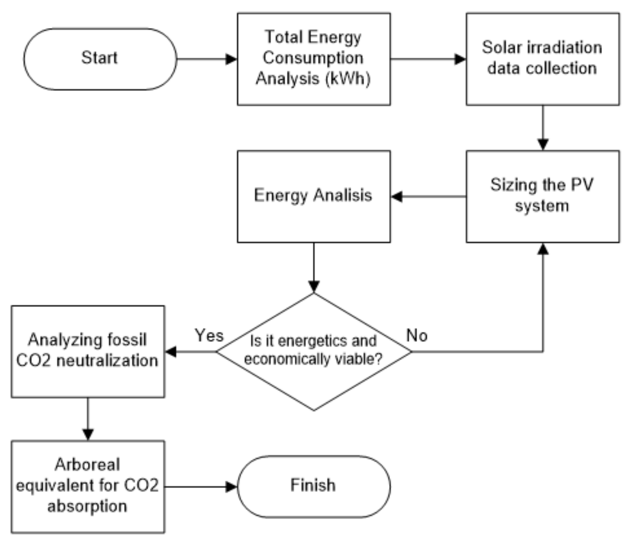

Fig. 1. A flowchart for illustrating the step-by-step process of the proposed methodology.

A. Initial Conditions

To establish the monthly demand and energy scenarios, a typical residential unit from Rio de Janeiro with an average monthly consumption (E_m) of 1,169.7 kWh was considered. This unit featured the following loads: lighting and power sockets, air conditioning, an auxiliary water heating system for the thermal reservoir, and a recharge station by Brazilian Standard ABNT NBR IEC 61851-22h for a 3.2 kW EV, all connected to the general switchboard presented in Fig. 2.

The EV used corresponds to the specifications of the Nissan Leaf and operates with a total range of 160 km and a battery capacity of 24 kWh with a single full charge. An average daily journey of 84 km and an approximately 4-hour nightly

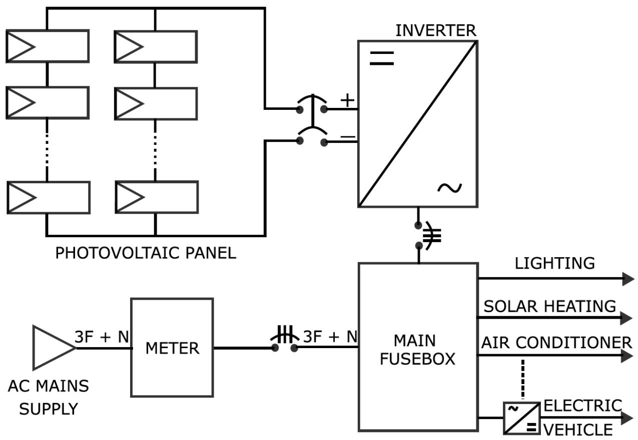

Fig. 2. Residential Electrical System containing PV and EV.

recharge period after the peak hour were adopted [20]. The daily average journey established is compatible with Rio de Janeiro users whose coverage allows for a reasonable return on an EV investment because Brazilian public policies for acquisition are still inceptive [21]. Those initial considerations led to the development of a monthly consumption profile, presented in Fig. 3, where the following curves are shown: residential consumption (without electrical vehicle), vehicle recharge consumption, and total consumption (household plus electrical vehicle).

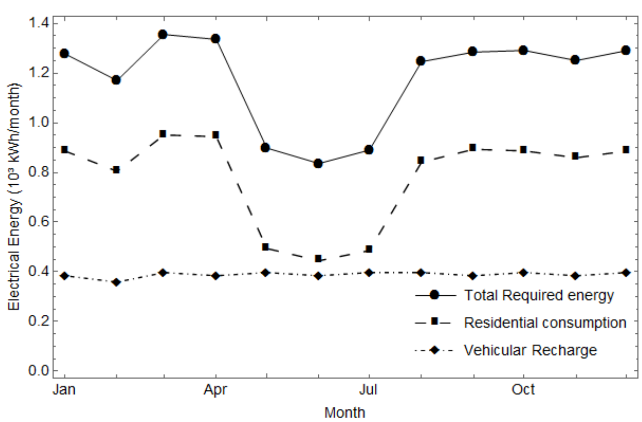

Fig. 3. Monthly consumption profile (10^3 kWh/mo).

B. Sizing the PV System

The criterion of average monthly consumption was adopted to model the PV generation system. In this criterion, the availability of 100 kWh (C_d) from the electrical system is deducted for three-phase consumers according to current regulations. The reference value of a monthly generated energy equals E_{Sm} = E_m - C_d = *1,069.7 kWh/mo*, which is equivalent to an average daily consumption E_{Sd} = *35.16 kWh/day*. The energy produced by a PV system in a single day (E_{Sd}) is determined by equation (1) and expressed in kWh:

$$E_{Sd} = n \cdot A_m \cdot \eta_m \cdot I_d \cdot PR \tag{1}$$

where *n* is the number of modules, I_d is the average daily solar irradiation (Wh/m^2/day), A_m is the module surface area (m^2), η_m is module efficiency (%) and *PR* is the system's Performance Ratio. The PV module temperature, inefficiencies in the inverter, mismatches, losses in the circuit and during the conversion from DC to AC power, partial irradiance utilization due to reflection from the module front surface, soiling or snow cover, system downtime, and component failures are just a few of the factors that can affect the rated output that are quantified by the Performance Ratio [22]. In this work, we adopted 83%. Based on the intended daily energy production value, E_{Sd}, expressed in equation (1), the number of required modules (*n*) can be calculated through equation (2).

$$n = \frac{E_{Sd}}{A_m \cdot \eta_m \cdot I_d \cdot PR} \tag{2}$$

Solar irradiation data for Rio de Janeiro have been provided by the Electrical Power Research Center (CEPEL)'s Sundata system, where the monthly values of average daily solar irradiation are presented, as illustrated in Fig. 4. For this paper, Canadian Solar Inc.'s 260 Wp module CS6K was chosen [23], whose parameters are presented in Table IV, with an A_m area of 1.637 m^2 and η_m efficiency of 15.88 %.

A simulation was conducted in PV-Sol where the program presented several combinations of modules and inverters from different manufacturers. The combination presented in this work was the one that offered the best cost-benefit ratio, i.e., the best cost per kWh generated for the on-grid system.

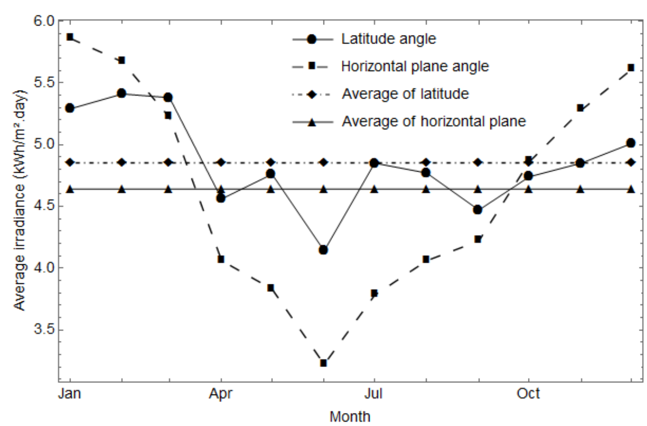

Fig. 4. Average Daily Solar Irradiation.

The energy produced by a single module every day is defined as E_m = A_m *x* η_m *x* I_d = *1.26 kWh/day*. An average 83% *PR* was adopted for the calculation of the number of modules, considering a non-shade scenario. In this condition, the number of required modules was determined using equation (2), resulting in 34 units.

The PV system inverter choice based on module and inverter manufacturer information was made upon the following criteria: the voltage of an open circuit set of modules is less than or equal to the maximum inverter input voltage, and the inverter input power, PE, around the set of modules' peak power [17], [24].

The set's open circuit voltage value depends on plaque arrangement. Serial modules are linearly displayed to form the so-called strings, and they determine the PV ensemble voltage, which is the inverter's input voltage, as in inequation (3):

TABLE IV
PARAMETERS OF CS6K-260P MODULES (25 ^{o}C)

Parameters	Data
P_p	260 W_p
V_{OCstc}	37.5 V_{cc}/module
I_{SC}	9,12 A
V_P	30.4 V_{cc}/module
I_P	8.56 A
β	-0.31 %/°C
η_m	15.88 %
A_m	1.637 m²

$$n_s \cdot V_{OCmax} < V_{inv-max} \tag{3}$$

where V_{Ocmax} is the open circuit voltage of a PV module at the lowest operation temperature, n_s is the number of linearly connected modules in a string and $V_{inv-max}$ is the highest inverter input voltage to be admitted. To obtain a module's open circuit voltage, V_{OC}, under standard conditions (25 °C), equation (4) is adopted:

$$V_{OC} = V_{OCstc(25^{\circ}C)}[1 + \beta(T - 25)] \tag{4}$$

where β is the open circuit voltage temperature (°C) and T is the operation temperature (°C). Since the modules' output voltage is strongly dependent on temperature, extreme summer and winter conditions are recommended for sizing purposes, particularly winter conditions, as this is when the highest open circuit voltages are obtained [22]. The string voltage must match the inverter's MPPT (Maximum Power Point Tracking [25]) voltage range. Failing that, the inverter may lose efficiency, which will eventually lead to disconnecting the relevant equipment item. Therefore, when temperature variations are considered throughout the year, the following inequation (5) is given:

$$\frac{V_{MPPmin}}{V_{Ptmax}} \leq n_s \leq \frac{V_{MPPmax}}{V_{Ptmin}} \tag{5}$$

where V_{MPPmin} and V_{MPPmax} are the respective operation minimum and maximum continuous current (c.c.) voltages to meet the inverter's MPPT, V_{Ptmax} and V_{Ptmin} are a module's maximum power voltage at, respectively, the highest and the lowest design operation temperatures. V_{Ptmin} and V_{Ptmax} values can be obtained from equation (4), replacing V_{Ocstc} with V_P. The system's peak power can be obtained from equation (6):

$$P_E = n \cdot P_p \tag{6}$$

where P_P is the maximum power expressed in this paper as peak-Watt (or W_p) supplied by a module and n is the number of modules. Since the maximum voltage is seldom attained, the inverter voltage Pinv can be significantly lower than the system's peak power [26]. An inverter should not operate far below the system's design power because of a sharp efficiency decrease [27]. In these circumstances, inverter power has been adopted in the following range $0.85P_E \leq P_{inv} \leq 1.15P_E$. The maximum inverter input current can be obtained from equation (7):

$$I_{inv} = I_{SC} \cdot n_p \tag{7}$$

where I_{inv} is the maximum inverter input DC current, I_{SC} is the PV module's short circuit current in standard condition, and n_P is the maximum number of parallel strings. Minimum and maximum design temperatures were adopted as 5 °C and 85 °C respectively. These temperatures indicated in the work are the minimum and maximum design temperatures adopted for photovoltaic systems in Rio de Janeiro, considering the temperature variation throughout the year, with the minimum occurring on winter nights and the maximum during summer days on the module surface. For an appropriate inverter selection, modules must be configured to meet operation specifications, abiding by the conditions settled in inequations (3) and (5) for maximum serial input power, and in equations (6) and (7) for inverter power in parallel configuration. For this paper, Fronius International's Fronius Symo 10.0-3-M inverter was selected with the parameters outlined in Table V. The inverter model chosen for this purpose is outfitted with two MPPT ports. The panel will feature two strings with 17 modules each, connected to the MPPT ports under the following configuration: MPP 1: 1 x 17 e MPP 2: 1 x 17.

TABLE V
PARAMETERS OF CS6K-260P MODULES (25 ^{o}C)

Parameters	Data
P_{inv}	10 kW
I_{inv}	27/16,5 A
V_{MPP}	270-800 V
$V_{inv-max}$	1000 V_{cc}
$V_{inv-min}$	200 V_{cc}

The maximum voltage of the strings' open circuit for lower operation temperature are 677.02 V for MPP 1 and MPP 2. The number of modules per string fell into the following range $11 < n_s < 24$. Inverter power is 113% of the arrangement's maximum peak power, and the inverter current is higher than the short circuit current of each string.

III. RESULTS

A. Energy Analysis

As previously stated, it is possible to make a monthly estimate of the average annual energy production of a PV system based on solar radiation. The estimated generation capacity of a properly sized system is presented in Fig. 5 and checked by PV-SOL software features. The required energy is the total monthly energy allowed for the complete charge of an EV plus the residential demand, which oscillates throughout the year. The results obtained through the presented methodology and the simulation in the PV-Sol software showed similar results in the monthly energy forecast.

The system is sized based on Brazilian net metering, where a three-phase consumer has a 100 kWh C_d quota, which is payable regardless of the use of electricity. To prevent losses, the difference between required energy (E_m) and generated energy (E_{sm}) should, ideally, be equal to the C_d quota. Monthly energy balances are presented in Fig. 6 and detailed

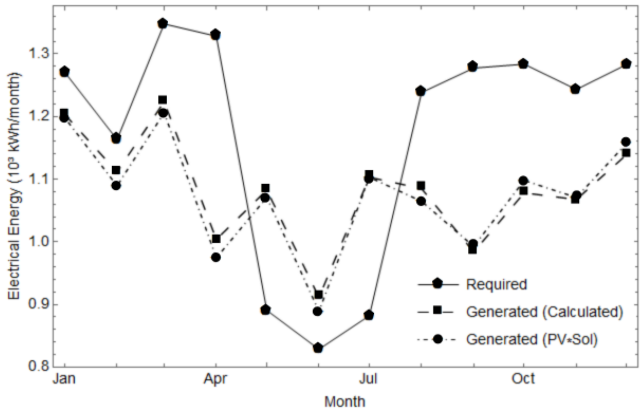

Fig. 5. Generated X required energy forecast.

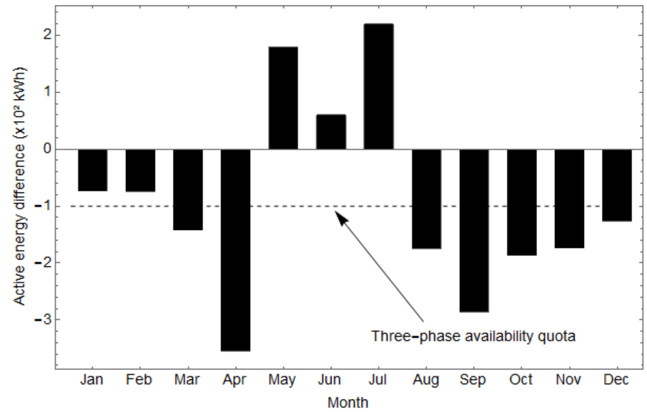

Fig. 6. Monthly energy balance.

in Table VI. In May, June, and July, there is a surplus and an accumulated bonus of 485.80 kWh of measured energy, but there is a total loss of 300 kWh because the C_d was not used. This loss represents energy that is paid for but is not used. In January and February, even with a deficit, there is a total 25.61 kWh loss due to partial use of C_d, as it is paid for 200 kWh of C_d, but 174.39 kWh is used. The energy loss for the month added up to a total of 325.61 kWh.

TABLE VI
MONTHLY ENERGY BALANCE (KWH)

Months	Cd (kWh)	Measured energy (kWh) Input to the grid	Consumed from the grid	Measured	Loss (kWh)
Jan	100	1,083.70	1,173.50	-89.80	10.20
Feb	100	987.41	1,072.00	-84.59	15.41
Mar	100	1,114.70	1,259.70	-145.00	0
Apr	100	911.67	1,260.70	-349.03	0
May	100	1,030.00	841.26	188.74	100
Jun	100	853.38	786.47	66.91	100
Jul	100	1,063.70	833.55	230.15	100
Aug	100	1,005.80	1,172.80	-167.00	0
Sep	100	922.47	1,207.80	-285.33	0
Oct	100	1,019.80	1,210.50	-190.70	0
Nov	100	979.16	1,162.90	-183.74	0
Dec	100	1,045.50	1,189.00	-143.50	0
Total	1200.00	12,017.29	13,170.18	-1,152.89	325.61

In Fig. 6, C_d is represented by the dotted line. In the months where the generation deficit was equal or greater than the C_d value, consumers pay for the factor energy used, which can be observed in March and April, and from August to December.

The data in Fig. 7 demonstrates a significant energy bonus during May, June, and July, attributed to the surplus in energy generation. As provided in ANEEL's Normative Resolution 687/2015, for compensation purposes, excess energy input to the grid is converted into credits and can be consumed in a matter of sixty months. The 485 kWh of accumulated bonuses will be used from August to December to cover the amount of energy consumed that exceeds the C_d availability quota, month by month. In August, for example, 67 kWh of the accumulated bonus will be used.

In Fig. 8, the dark fields represent the energy that was paid for by the local energy service company. Fig. 8 presents energy accumulation in May and June (255.65 kWh) and the energy from May and June accumulated in July when there is a total bonus of 485.80 kWh. This accumulated energy bonus was used as a rebate for the generation deficit from August to December, whose due payments to the energy service company will be only the C_d monthly quota. After rebating the credits, a surplus of at least 15.53 kWh will be obtained, to be used in the following year.

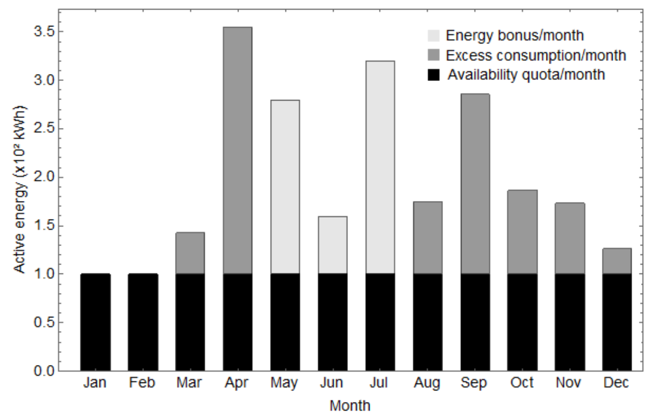

Fig. 7. Energy balance and availability cost.

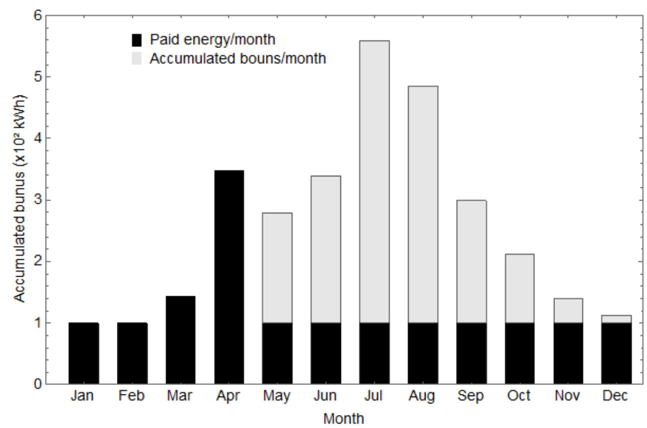

Fig. 8. Bonus accumulation and use.

B. Analyzing Fossil CO2 Neutralization

1) Emissions Neutralization Methodology: The environmental performance of the Nissan Leaf EV was conservatively compared to that of ICV Nissan New March 1.0, which is a low-emissions level vehicle according to the Brazilian Vehicle Labeling Program (PBEV). This analysis is considered robust and relevant, provided C gasoline is used in a 25% mix with ethanol. According to the PBEV, Nissan New March's main emission factors are 96 g/km of CO_2 0.003 g/km of nitrogen oxides (NOx), and an average consumption of 0.077 liters of gasoline per kilometer in urban centers. According to the National Petroleum Agency (ANP), type C gasoline density and calorific capacity are, respectively, 754 kg/m^3 and 10,200 kcal/kg. Bottom-up estimated annual ICV emissions are presented in [13]. In this work, the methodology is simplified to assess emissions (G_{ev}) from a single ICV and presented in equation (8).

$$G_{ev} = fe \cdot l \cdot d \tag{8}$$

where *fe* is the ICV's emissions factor, considered in tons per km, l is the extension of daily travel, in km, and d is the number of days when the vehicle travels that distance l. According to the National Energy Balance, in 2015 use of energy coming from Brazilian thermoelectrical power plants was the highest, characterizing the worst scenario for this analysis. Based on that assessment, an emissions factor f_s was used for the Interconnected National System (SIN) of 0.139 tCO_2 / MWh and the total avoided fossil CO_2 emissions were calculated as:

$$G_s = \begin{cases} \frac{f_s \cdot (E_{ger} - \Delta E)}{1000} + (G_{ev} - \frac{f_s \cdot E_{rec}}{1000}), & \Delta E > 0 \\ \frac{f_s \cdot E_{ger}}{1000} + (G_{ev} - \frac{f_s \cdot E_{rec}}{1000}), & \Delta E < 0 \end{cases} \tag{9}$$

where G_s is the total avoided fossil CO_2 emissions from a PV and EV combination, E_{ger} is the energy generated by the PV system, E_{rec} is the energy used for electrical vehicle recharge, ΔE = E_{absor} - E_{ger} is the monthly net energy compensated by the service grid, and E_{absor} is the energy absorbed from the grid. In equation (9), the E_{rec} corresponding portion is considered as nighttime recharge (later than 11 pm), using grid power.

In [28] describes a mathematical model to express carbon neutralization in numbers of equivalent trees necessary to absorb fossil CO_2 emissions, according to equation (10),

$$N_a = \frac{G_s \cdot fcp}{f_{fix}} \tag{10}$$

where N_a represents the number of trees to be planted in a certain area, f_{cp} is the seedling loss compensation factor, usually considered as 1.2, and f_{fix} is the biomass carbon fixation factor referring to the tree of choice, as per equation (11):

$$f_{fix} = \frac{I_{ma} \cdot TC \cdot f_{cc} \cdot t_a}{f_{ref}} \tag{11}$$

where I_{ma} is the average annual increase of living biomass above and below ground, composed of accumulated dry matter on plant site every year, *TC* is the carbon content of annually accumulated dry matter, f_{cc} is the carbon mass conversion to CO_2 equal to the fraction 44/12, t_a is the time in years to fully neutralize total emissions, and f_{ref} is the reference factor expressed by the number of tree species per plant area. According to the Intergovernmental Panel on Climate Change data (IPCC 2003), the value adopted for I_{ma} in tropical and subtropical 20+ year-old forests is 2 tons of dry matter / (ha.year). Since the reference trees here reach full growth at the end of a 20-year period after planting, calculated absorption will reach its peak at the end of that period, where is equal to t_a 20. Concerning the carbon content, a proportion of 50% was established and the f_{ref} value corresponds to 1,667 trees/ha, according to [23]. The selected tree species was Pinus [28], known to be adaptable to many different regions in Brazil. The area to be considered for planting, A_{pt}, that tree species can be estimated by equation (12):

$$A_{pt} = \frac{N_a}{f_{ref}} \tag{12}$$

2) Analysis of Avoided Emissions and Carbon Neutralization: According to equation (10), it is possible to predict the monthly avoided emissions by considering the calculated PV generation, consumption, energy deficit, fuel used in the ICV, and monthly vehicle recharge energy. Fig. 9 presents monthly amounts of avoided fossil CO_2 emissions (G_s), based on the values presented in this paper. In April, when complementary grid power achieved its peak, avoided emissions (G_s) were lower. The proposed methodology reduces emissions by 4.07 tons of fossil CO_2 / year.

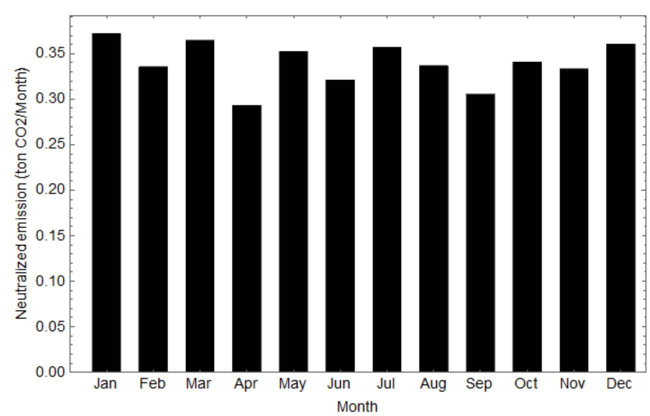

Fig. 9. Monthly avoided CO_2 emissions.

Applying the equations to describe the methodology used in this paper allows an interpretation of carbon neutralization in terms of equivalent reforestation. Applying equation (11), avoided emissions are observed to balance fossil CO_2 absorption by 111 adult Pinus-type trees that occupy a planted area of 666,33m², from equation (12). In Fig. 10, a comparison is presented between avoided emissions within the proposed system and CO_2 absorption by the trees. The trees increase their fossil CO_2 absorption capacity according to their growth, reaching maximum absorption after 20 years of age, whereas the proposed PV + EV system presents the same capacity from its very inception. According to the conditions adopted in this work, the 111 planted trees will achieve fossil CO_2 absorption equal to the implanted system's s in a 20 year life cycle.

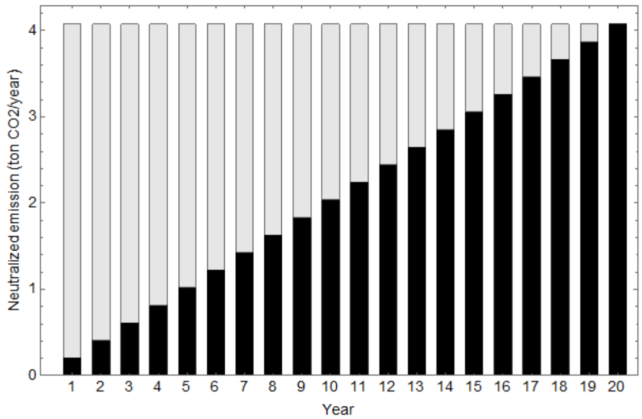

Fig. 10. Comparing annual CO_2 neutralization by trees and EV.

Remarkably, when expressing the annual EV avoided emissions, the values presented here in terms of equivalent reforestation do not assume replacing one endeavor with the other. These results highlight favorable attributes to electrifying road transport, which cannot be found in ICV, as they are to the performance of renewable microgeneration of lower environmental impact electricity.

IV. Conclusion

Residential microgeneration of photovoltaic electricity associated with electric vehicle charging provides relevant results.

This conclusion is further reinforced by the ANEEL Normative Resolution No. 1.059/2023, which establishes general conditions for microgeneration and the energy compensation system, allowing residential installations to become electricity producers as well.

Using the theoretical model developed in this study, the monthly generation forecast was close to that presented by the PV-SOL model. Considering the availability rate as the basic tariff, this energy analysis showed that an adequately sized system is capable of providing a minimum acceptable surplus at the end of the period due to the compensation resource.

The environmental analysis conducted with this model predicted a significant value of 4.07 tons of avoided fossil CO_2 emissions annually. Compensating for avoided emissions in terms of necessary reforestation demonstrated that this installation is equivalent to the absorption of fossil CO_2 by approximately 111 adult Pinus trees, occupying a planted area of approximately 666.33 m^2.

This article presents arguments justifying the strengthening of public policies in favor of the electrification of road transport and the microgeneration of energy from renewable sources.

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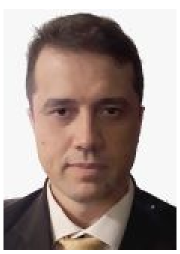

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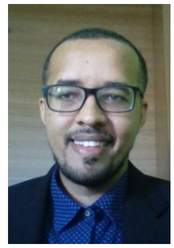

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