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Probabilistic Approach to Integrate Photovoltaic Generation into PEVs Charging Stations Considering Technical, Economic and Environmental Aspects

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Abstract: This paper investigates the integration of a photovoltaic system into plug-in electric vehicles charging stations in a university campus building located in Belem, Brazil, considering technical, economic, and environmental impacts in a probabilistic approach. Monte Carlo method is implemented to probabilistically estimate output variables, representing uncertainties from input data such as solar generation, vehicles demand and building load. Simulations are based on local irradiance data and electricity demand measurements collected by a local monitoring system installed in the building. The analysis comprehends a study time horizon of 10 years and evaluates transformer load and voltage level, carbon emissions avoided, and the financial feasibility of the project. Results show the connection of a PV system with penetration level of 15.6% can significantly reduce transformer overload occurrence by 69% and decrease overload duration time on average from 4 to 1 h at 10th year. PV system can reduce PEV CO_2 emission by 97.4% on average compared with internal combustion engine vehicles. From a financial perspective, the project is feasible and economically attractive with a payback time that ranges from 6 to 8 years, being an attractive solution to the Amazon region to support a cleaner energy matrix.

Keywords: probabilistic analysis; Monte Carlo; plug-in electric vehicles; economic feasibility; photovoltaic system; CO_2 emissions

1. Introduction

The transport sector is a major use of fossil fuel, increasing greenhouse gas emission and the global warming. In 2019, the transport sector produced 8.2 Gt of CO_2 emission, representing 24% of direct emissions from fuel combustion [1]. Due to the necessity to reduce air pollution, the number of plug-in electric vehicles (PEVs) has been continuously increasing in the last years, as well as the use of renewable energy sources. In 2019, the global stock of electric cars reached 7.2 million and the number of charging points worldwide was approximately 7.3 million, representing an increase of 60% from the year before [2]. In this same year, renewable energy installed capacity had its highest increase and grew 200 GW, in which more than 50% were from photovoltaic generation [3].

Despite the environmental benefits electric vehicles can bring, their large-scale integration on distribution system can cause several negative impacts such as increased system peak demand, transformer overload operation and power quality problems. Several papers have been proposed addressing the connection of electric vehicles in power system, and most of them analyze their impact on grid, use PEVs on the vehicle-to-grid (V2G) operation mode, and propose smart charging algorithms to mitigate their effects. Reference [4] proposes a charging coordination algorithm using PEVs in both operation modes grid-to-vehicle (G2V) and V2G to reduce power losses, maintain voltage profile and balance load current. In [5], PEVs charge/discharge pattern is optimized, and V2G operation is analyzed in an island electric grid in Spain. Reference [6] proposes a smart charging algorithm to reduce electricity consumption costs and prevent transformer overloading integrating a battery energy storage system and photovoltaic generation into the charging station.

Although a huge advance has been made, PEVs smart charging and V2G operation mode are at an early stage of development and some barriers still need to be addressed. To effectively apply these concepts, it is essential to have a safe communication technology between PEVs and electric vehicle supply equipment (EVSE), following strict protocols and standards to avoid cyber-attacks and guarantee personal data protection [7]. Another important issue is that V2G operation still requires further advances to reduce battery degradation and gain consumer acceptance [8]. Also, the presence of an aggregator would be required to control the bi-directional power flow in the system.

In this scenario, the integration of photovoltaic (PV) generation into PEVs charging station infrastructure can be a possible solution to properly integrate PEVs on grid and reduce their negative impacts. It could reduce carbon emission and system peak demand, avoiding transformer overload condition. Some studies have been developed addressing this issue. Reference [9] proposes the integration of a solar plant to a PEV parking lot to reduce power consumption and losses considering various operating conditions. In [10], authors study the impact of integrating solar photovoltaic panels with charging stations into a residential system in Kuwait considering reactive power compensation. Reference [11] proposes the design of a fast-charging station with storage system, solar and wind generation to improve the profitability and reduce energy consumption from the grid. In [12], authors optimize the use of PEVs, photovoltaic generation and energy storage batteries in a building in the day-ahead electricity market to maximize the local profit.

Although some research has been done, the use of PV generation into PEVs charging infrastructure have some challenges that need to be addressed. The output power of photovoltaic generation may have diurnal and seasonal fluctuations and electric vehicles demand also have an uncertain pattern that varies with drivers' behavior and preferences. Due to the difficulty in supply-demand matching, this problem must be modeled based on stochastic approach exploring different scenarios to account these variabilities. Besides, the massive use of electric vehicles is not a solution itself that should reduce carbon emission, since it depends if the source of electricity used to charge vehicles is green or comes from non-renewables sources. Then, it is important to study the impact of using PV generation and electric vehicles to reduce carbon emission and achieve a sustainable electric mobility [13].

This paper aims to assess the integration of a PV system with electric vehicles charging stations in a university campus building located in Belem, Brazil. A case study is performed based on city irradiance data and building electricity demand measurements collected by a local monitoring system. The study includes technical, economic, and environmental analysis, evaluating the impact on transformer load and voltage, financial feasibility of the project and carbon emissions avoided, constituting a probabilistic problem. Monte Carlo simulation is employed to probabilistically estimate those outputs taking into consideration uncertainties due to PV generation, building and PEVs demand. The originality and main contributions of this paper are:

- The study is based on real data collected with an advanced metering infrastructure system installed in a University Campus located in the Amazon region, in northern Brazil;
- Unlike other studies, PEVs demand is represented individually instead of aggregated, considering important parameters to each vehicle, such as arriving time and battery initial state-of-charge;
- Uncertainties due to solar generation, PEVs and building demand are considered in the model in a stochastic manner, using Monte Carlo simulation;
- The analysis simultaneously incorporates technical, economic and environmental issues allowing a global view of the problem to power systems planning purpose, showing the benefits of using green technologies;
- Power system is modeled and considered in simulations through power flow analysis.

The rest of this paper is structured as follows. Section 2 shows the building electricity demand data and the University Campus grid configuration. In Section 3, the probabilistic modeling with Monte Carlo method is presented. Section 4 discusses simulation results and Section 5 addresses the main conclusions of the paper.

2. Case Study: Building Demand Data

Brazil has high solar potential, with irradiance levels relatively stable through the whole year. In 2019, photovoltaic generation installed capacity had an increase of 37.6% (675 MW) compared to the previous year, and the solar photovoltaic market is expected to keep growing. The electric automotive market in Brazil is also projected to increase in the next years, although still being dominated by the ethanol industry, which accounts for 45.4% of the country's CO_2 emission [14].

In this context, this work analyzes the integration effects of a grid-connected photovoltaic system with four electric vehicle charging stations installed at the central library of the main campus of Federal University of Para, in the Amazon region of Brazil. Installing charging points on campus is a great addition to any institution from a business point of view, showing social responsibility and environment commitment. The main campus structure includes 84 lecture and administrative buildings, multiple libraries, and a hospital. Electricity is supplied to the university through an overhead power line at 13.8 kV, and the library building is equipped with a 225 kVA 13.8 kV/127 V transformer, as illustrated in Figure 1.

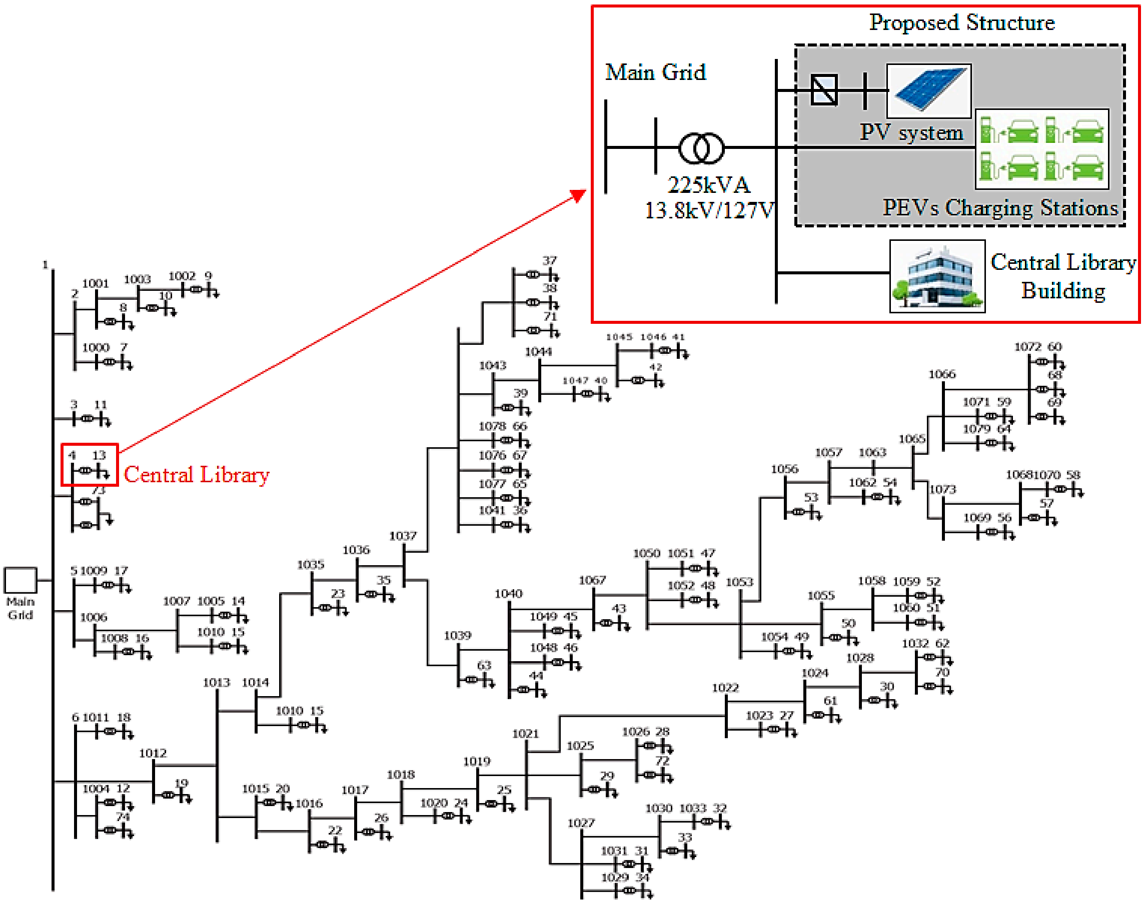


Figure 1. Single-line diagram of campus distribution system.

The central library building has two floors and occupies an area of 6177.81 m^2 as shown in Figure 2. It has more than 67 employees and the opening hours are from 8 h to 22 h from Monday to Friday, and from 8 h to 14 h on Saturday. An advanced metering infrastructure system named SISGEE was installed at the buildings [15] and the monthly peak load registered in 2018 is shown in Figure 3a. The building has an administrative profile and its electricity demand includes cooling, lighting, and the use of electrical appliances such as computers, printers, and photocopiers. The demand is influenced by different features, such as regular class period and vacation/holiday period. The academic year calendar at the university is divided into two semesters. The first semester classes usually start on March and end in June. The second semester classes start on August and end in December.

Figure 2. Central Library building on main campus.

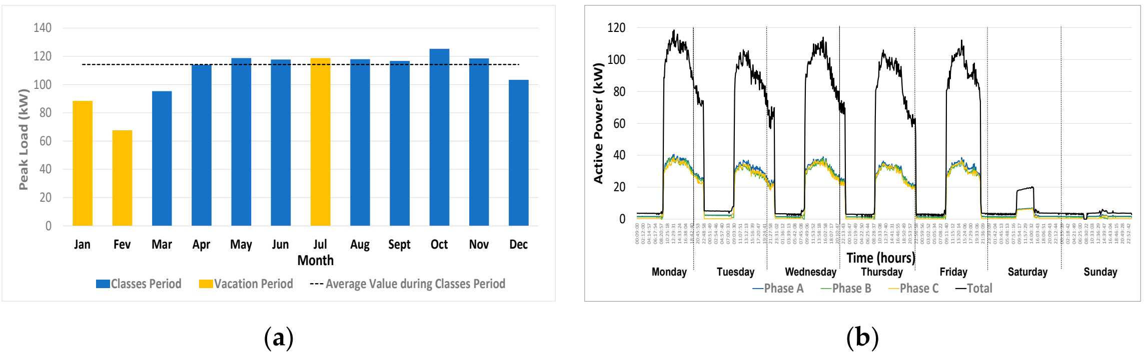


Figure 3. Building demand in 2018. (**a**) Monthly peak load; (**b**) Daily demand during 1-week in November.

The electricity consumption during vacation period is considerably lower than during the classes period, except in July of 2018, since in this year classes were extended until July 17th. Figure 3b presents the active power measured in the three phases of the transformer that supplies the building for 1-week period from 19 to 25 November 2018. The energy consumption is higher between 9 h and 22 h during weekdays, and much lower on weekends. The distribution transformer at the central library building uses only 55% of its rated capacity but may become overloaded with PEVs demand. The load profile of this week was adopted as the base load to perform all analyses since it follows the average peak load during the classes period.

3. Probabilistic Modeling

Since many uncertainties are involved in this problem, Monte Carlo simulation is applied according to Figure 4. All input variables with inherent uncertainties are represented by a probability density function (PDF) [16]. Random values are sampled following their input PDF several times, and outputs values are obtained and recorded. Each set of samples is called an iteration and the result is a probability distribution of possible outputs. Monte Carlo simulation informs all possible output values of the model and their probability of occurrence. The methodology applied includes technical, economic, and environmental analysis. Technical analysis evaluates the impact on transformer load and voltage profile, and the possible benefits that could be obtained installing PEVs charging stations and PV system. The economic approach investigates the financial feasibility of the project using economic indicators, and the environmental analysis estimates carbon emissions avoided with the installation of PEVs charging stations and PV system.

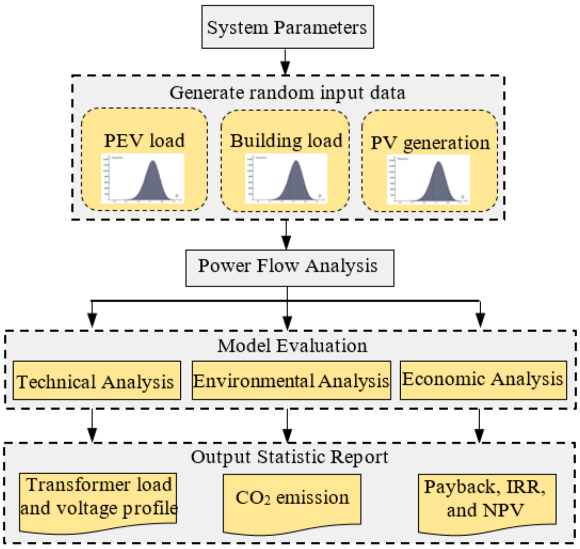


Figure 4. Methodology applied.

System voltage is obtained with power flow simulations, and transformer load (P^t_{transf}) is obtained as in Equation (1):

$$P^t_{transf} = P^t_{build} + P^t_{pev} - P^t_{PV}, \; \forall \, t \, \in \, T, \tag{1}$$

where P^t_{build} is building demand, P^t_{pev} is PEV total demand, and P^t_{PV} is photovoltaic generation at time t, all given in kW.

The number of iterations needed to achieve convergence in Monte Carlo method was 3000. All steady-state simulations are performed using MATLAB and PSAT software [17,18]. Input variables modeling are presented next.

3.1. Building Electricity Demand

Based on the average load profile during classes period, building demand is projected 10-years ahead as shown in Figure 5. This projection is based on a yearly increase of 6.0% established from historical data analysis. To consider uncertainty, building demand is modeled by a normal probability density function for a 24-h period, which is commonly used to model electricity load, with mean following the hourly demand and standard deviation of 2% [19].

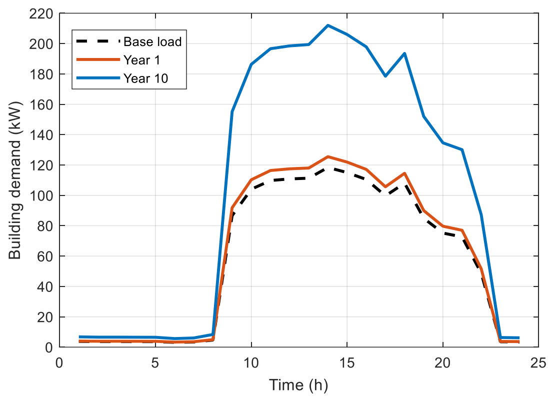


Figure 5. Building demand projected to 10-years ahead.

3.2. Electrical Vehicle Demand

Instead of aggregated, PEVs demand is modeled individually to achieve a more precise representation. PEVs daily demand curve can be obtained from three information: start charging time, the required time to charge each vehicle and the charging power. This study considers that vehicles start charging immediately after arriving at the building. The start charging time (T_{start}) is modeled based on the occupation of the building observed over several weeks, which indicated the library has a bigger occupancy rate around 14 h and is open between 8 h and 22 h during the week. Based on that, random numbers are generated from the normal distribution with mean equal to 14 h and standard deviation of 2 h as shown in Figure 6. The battery initial state-of-charge (SOC_i) can be calculated using the driving distance (d) as in Equation (2) [20,21]:

$$SOC_i = max\left\{SOC_{min}, 1 - \left(\frac{d \times E}{C_b}\right)\right\}, \quad (2)$$

where E is the battery energy consumed in kWh/km, C_b is the battery capacity in kWh, and SOC_{min} is the minimum SOC assumed as 5%.

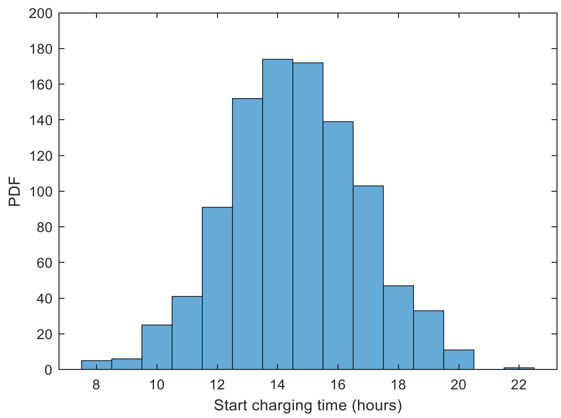
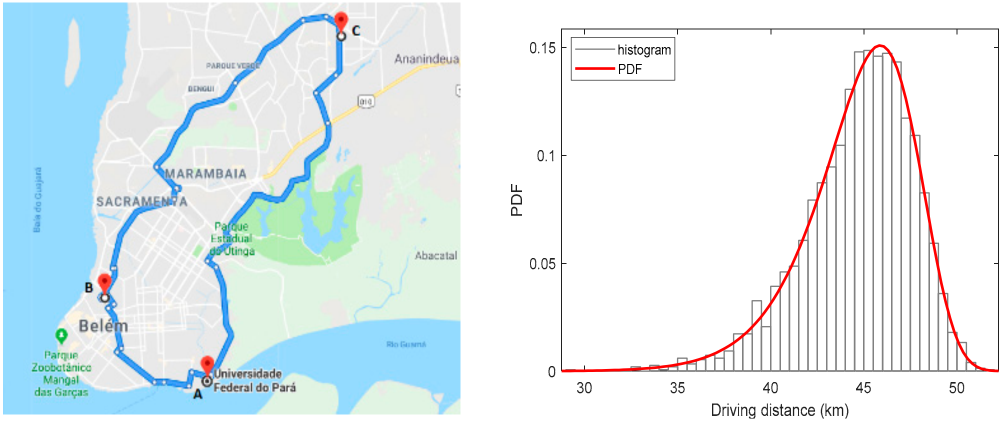


Figure 6. Normal PDF of start charging time.

Since there is no statistical data of daily distance traveled by domestic vehicles in Brazil, this parameter is modeled by a Weibull PDF, which is commonly used to model driving distance parameter [22,23]. Based on the city's typical route, mean value of 46 km was adopted as illustrated in Figure 7. In this route, the driver leaves the university (point A), stops at point B which could be a grocery store or a mall, and goes home (point C). In the next day, the driver returns to the university (point A) and charges his vehicle.



(**a**) (**b**)

Figure 7. Driving distance modeling. (**a**) Driving route; (**b**) Weibull PDF.

The energy required E_{req} to charge the vehicle can be evaluated by Equation (3), adopting efficiency η equal to 0.8:

$$E_{req} = (1 - SOC_i) \times (\mathrm{E}/\eta), \tag{3}$$

The necessary time to charge the vehicles (T_{charge}) is obtained by Equation (4). PEVs are modeled as constant power loads, charged with P and unity power factor:

$$T_{charge} = \frac{E_{req}}{P} \tag{4}$$

The aggregated PEV demand (P^t_{pev}) can be obtained taking in account each PEV demand j at time t (P^t_{PEVj}) as in Equation (5). This study considers PEVs are charged at Level 2 (6.6 kW), which is adequate to public buildings [24,25] Two types of vehicles are adopted with parameters presented in Table 1: Nissan Leaf and Chevrolet Bolt [26,27].

$$P^t_{pev} = \sum\nolimits_{j=1}^{N} P^t_{PEVj}, \; \forall\, t \in T, \tag{5}$$

Table 1. PEV Battery Specification.

Vehicle Battery Specification	Nissan Leaf	Chevrolet Bolt
Battery Energy (E)	0.1058 kWh/km	0.1567 kWh/km
Battery Capacity (C_b)	40 kWh	60 kWh

3.3. Photovoltaic Generation

Solar irradiance is commonly represented by a Beta PDF as shown in Equation (6):

$$f^t_s = \begin{cases} \frac{\Gamma(\alpha^t+\beta^t)}{\Gamma(\alpha^t)\Gamma(\beta^t)} \times \left(s^t\right)^{(\alpha^t-1)} \times \left(1-s^t\right)^{(\beta^t-1)}, & 0 \le s^t \le 1,\ \alpha^t, \beta^t \ge 0 \\ 0 & , otherwise \end{cases}, \tag{6}$$

where s^t is solar irradiance in W/m^2, Γ is Gamma function, α^t and β^t are the shape parameters calculated based on solar irradiance mean μ^t and standard deviation σ^t at time t, as shown in Equation (7):

$$\beta^t = \left(1-\mu^t\right) \times \left[\frac{\mu^t\left(1-\mu^t\right)}{\left(\sigma^t\right)^2} - 1\right] \text{and } \alpha^t = \frac{\mu^t \beta^t}{\left(1-\mu^t\right)}, \tag{7}$$

This paper uses data of ambient temperature and solar irradiance from the city of Belem (1°501′ S, 48°449′ W), Brazil, available at National Renewable Energy Laboratory (NREL) website [28]. Based on irradiance historical data, the hourly mean and standard deviation are estimated to capture solar irradiance oscillations, obtaining Beta PDF parameters. Then, irradiance random values are generated according to the PDF to each hour of the day. The PV system output power can be obtained by Equations (8) and (9) [29]:

$$P^t_{PV}\left(s^t\right) = \left(\frac{P_n\, s^t}{1000}\right) \times \left[1 + \lambda\left(T^t_{cell} - 25\right)\right], \tag{8}$$

$$T^t_{cell}\left(s^t\right) = T^t_a + \frac{s^t}{800}(NOCT - 20), \tag{9}$$

where s^t is the irradiance at time t, P_n is nominal power of the PV module in W, λ is the temperature coefficient of power in %/°C, T^t_{cell} is cell temperature, T^t_a is ambient temperature, and $NOCT$ is the nominal operating cell temperature (45 °C), all temperatures in °C.

Figure 8 shows the monthly solar irradiance and temperature in Belem. The region where Federal University of Para is located is privileged in terms of solar irradiance, with a maximum value of 5.38 kWh/m^2/day for the month of September and a minimum of 4.4 kWh/m^2/day for the month of February [30]. The ambient temperature has little variation, in a rage of values from 24.5 °C to 32.8 °C. The number of required PV panels is obtained as follows in Equation (10):

$$N°.\, of\ Panels = \frac{E^{max}_d}{\eta_{inv} \times (1 - L) \times P_{kWp} \times PSH}, \tag{10}$$

where E^{max}_d is the maximum daily energy consumed from PEVs in kWh, η_{inv} is the inverter efficiency, P_{kWp} is the module peak power, L is the losses coefficient, and PSH is the peak-sun hour.

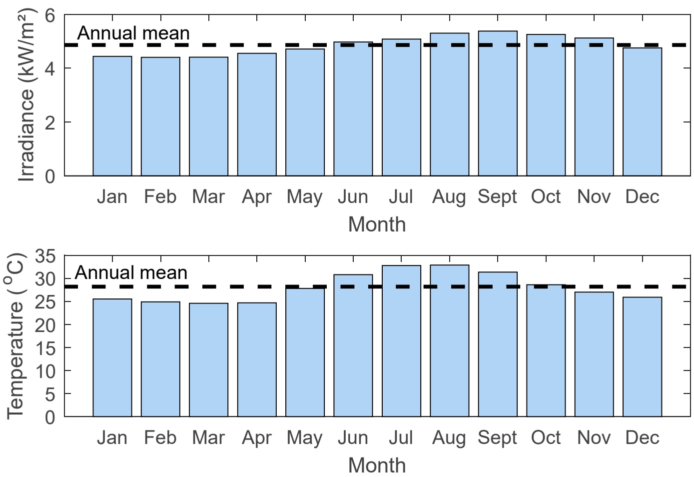


Figure 8. Monthly averaged solar irradiance and temperature in Belem, Brazil.

The photovoltaic system proposed in this study is composed by BYD 335P6D-36 modules of 335 Wp and Fronius inverter model 27.0-3-S, with specifications listed in Table 2 [31,32]. The average irradiance was used to obtain the peak-sun hour (PSH), and around 105 modules are required to ensure system operation throughout the year. The maximum number of PV modules in series in a string is calculated by Equation (11), and the maximum number of strings connected to the inverter is given by the Equation (12) [33]:

$$N_{series} < \frac{V^{max}_{INV}}{V_{oc}}, \tag{11}$$

$$N_{str} = \frac{I^{max}_{INV}}{I_{sc}}, \tag{12}$$

where V_{INV}^{max} is the maximum inverter DC input voltage, V_{oc} is the module open circuit voltage, I_{INV}^{max} is maximum inverter DC current, I_{sc} is the module short circuit current.

Table 2. Inverter and PV Module Specifications.

PV Module	
Peak Power	335 W
Rated voltage V_{mp}	37.35 V
Rated current I_{mp}	8.97 A
Open circuit voltage V_{oc}	47.28 V
Short circuit current I_{sc}	9.39 A
Efficiency	17.4%
Dimension	1.95 m × 0.98 m
Inverter	
Maximum PV power	37.8 kW
Nominal power	27 kW
MPPT voltage range	580–850 V
DC input voltage range	580–1000 V

According to equipment specification, the proposed PV model arrangement consists of five parallel lines and each line has 21 panels connected in series, with a total peak power of 35.17 kW, using a total area of 200 m^2. Operation at unity power factor was assumed, which is normal for PV inverters.

4. Simulation Results

4.1. Technical Analysis

This section analyzes potential impacts on distribution transformer load and voltage for a study time horizon of 10 years. The results consider first the connection of PEV charging stations, and then the connection of PEV charging stations combined with the proposed PV generation system.

4.1.1. PEV Charging Stations

This case supposes the connection of 4 PEV charging stations at the central library building without the installation of a PV system. Figure 9 shows the cumulative distribution function (CDF) of transformer peak load during a typical weekday, for year 1 to 10. The peak hours on building's load coincides with the period most PEVs are charging, leading to transformer overload condition. Simulation results show that at year 8, the probability of transformer overload is 5.36%, at year 9 is 77.9%, and at year 10 is 100%, which is unacceptable.

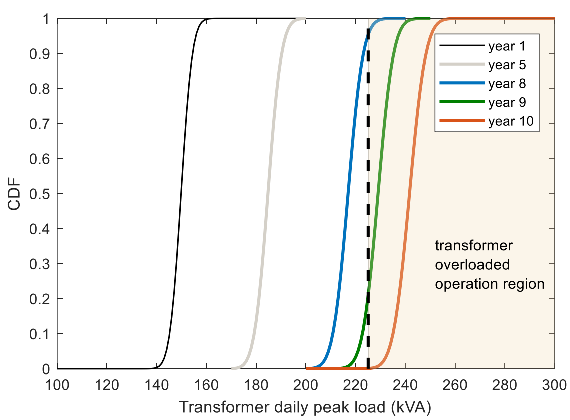


Figure 9. CDF of transformer peak load for different years.

Since year 10 is the most critical scenario, it will be analyzed in more details. Figure 10 shows transformer peak load boxplot during a typical weekday at year 10. Boxplot is a graphical representation that displays the distribution of variables. The box contains 50% of data, the lower and upper boundaries of the box are the first quartile and the third quartile, and the median is represented by a solid line across the box. The lines that extend from the box to minimum and maximum values are known as whiskers.

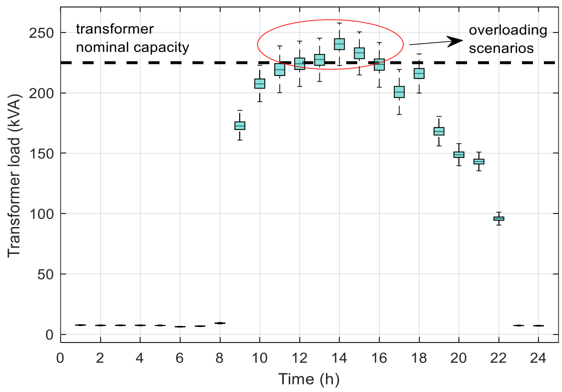


Figure 10. Boxplot of transformer load at year 10.

Results indicate transformer load exceeds its nominal capacity between 11 h and 16 h, and in most cases transformer remains overloaded during 4 h according to Figure 11. Transformer overloaded operation is only acceptable during emergency or contingency conditions, and for a small period. In this case, since the time transformer remains overloaded is long, it can cause equipment premature aging, not being encouraged. This restriction may limit the installation of PEVs charging stations at this building if no additional measures are adopted, as upgrading transformer, or installing a PV generation system.

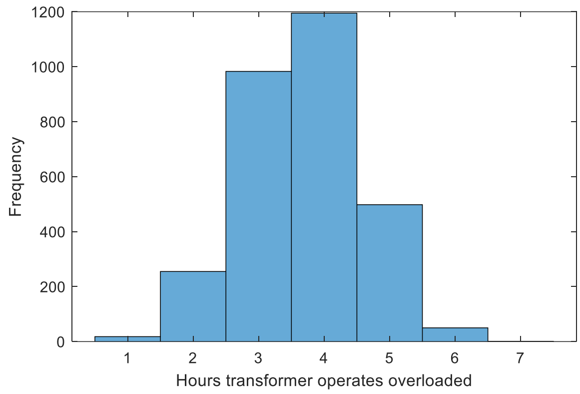


Figure 11. Histogram of number of hours transformer operates overloaded at year 10.

The voltage on the low side of transformer is not affected even when machine operates overloaded. The effect of PEV demand on transformer voltage profile is unnoticeable since this bus is electrically close to the feeding point. To illustrate this, Figure 12 presents the voltage profile at year 10, when PEVs are connected in two different places: close to the feeding point at location 1 (central library building), and far away from the feeding point at location 2.

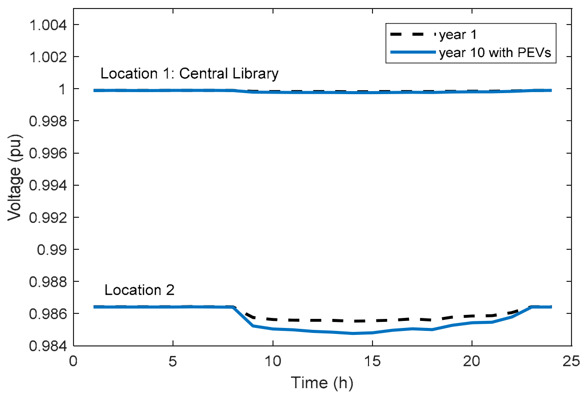


Figure 12. Voltage at low-voltage side of transformer.

4.1.2. PEV Charging Stations with PV Generation

This case considers the installation of four electric vehicles charging stations and a PV system in the central library parking lot. Results are referred to the most critical year (year 10) and a sensibility analysis is performed considering two cases with different photovoltaic penetration levels (PL):

- Case 1: PL = 15.63% (35.17 kW);
- Case 2: PL = 23.52% (52.93 kW).

The first case refers to the PV system projected to supply 100% of PEVs electricity demand. The second case refers to a bigger PV system, projected to supply 100% of PEVs electricity demand and part the building's electricity demand. This study defines the PV penetration level as the ratio of PV peak power to the transformer nominal capacity, being calculated by Equation (13) [34].

$$PL = 100 \times \frac{PV\ Peak\ Power}{Transformer\ Rated\ Capacity}, \quad (13)$$

Figure 13 shows the boxplot of transformer peak load for both PV penetration levels during 24 h at year 10. The probability of transformer overloading is considerably reduced as PV peak power increases. In Case 1, transformer overloading probability is 31.2% and in Case 2, it is 8.2%. Figure 14 illustrates the cumulative distribution function of transformer daily peak load for both PV penetration levels. In both cases, transformer operates overloaded only for 1 h in most scenarios, as shown in Table 3. Thus, both PV penetration levels are acceptable, and the installation of a PV system of 35.17 kW to 52.9 kW can help to reduce transformer overload occurrence.

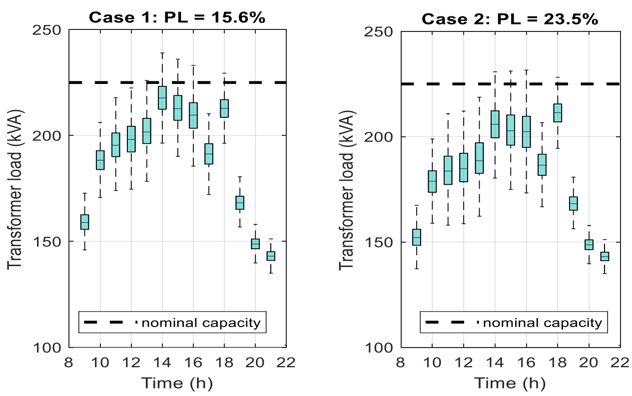


Figure 13. Boxplot of transformer load at year 10.

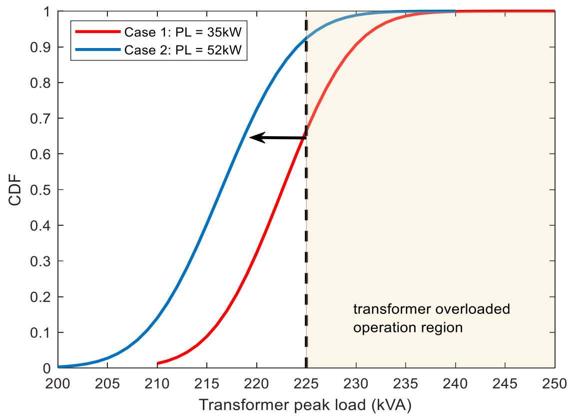


Figure 14. Transformer peak load CDF for two PV levels at year 10.

Table 3. Probability of Number of Hours Transformer Overloads.

	Number of Hours Transformer Operates Overloaded		
PV Level	1 h	2 h	3 h
PL = 15.6%	88.5%	11.1%	0.4%
PL = 23.5%	97.2%	2.8%	0%

4.2. Economic Analysis

In this section, cash flow analysis is applied, and to check the viability of the investment some financial indicators are evaluated: net present value (NPV), internal rate of return (IRR) and payback (PB) [35]. Net present value is a financial indicator extensively used across finance to analyze the profitability of an investment, accounting the difference between all cash inflows and cash outflows during a period of time, as shown in Equation (14):

$$NPV = -C_0 + \sum\nolimits_{t=1}^{T} CF_t(1+r)^{-t}, \tag{14}$$

where C_0 is the investment cost in $, T is the number of years the investment is analyzed, r is the discount rate in %, and CF_t is the cash flow in $, calculated by the difference between incomes and expenses at year t.

The internal rate of return is an indicator used to obtain the profitability of an investment. It is the discount rate that makes the NPV of all cash flows equals to zero, as shown in Equation (15). If IRR exceeds the minimum attractiveness rate (MAR), the project is more likely to be accepted. An equity rate of 7% was adopted as the minimum attractiveness rate since this investment does not have external funding [36]. The payback (PB) period is commonly used to evaluate investments and is the amount of time needed to earn back the cost of an investment. It is calculated accumulating the net cash flow until it becomes a positive number. A shorter payback period means the investment will be quickly recovered and is preferable:

$$-C_0 + \sum\nolimits_{t=1}^{T} CF_t(1+IRR)^{-t} = 0, \tag{15}$$

The duration time of the project is 25 years, which corresponds to solar panels lifetime. Equipment's costs and rates were collected from manufacturers datasheet and website, which are listed in Table 4 [37–40]. The electricity time-of-use (TOU) rate adopted by local utility company is presented in Table 4. Free parking is available on campus throughout the day, which is a common practice in Brazil. This study considers university will also offer free charging to electric vehicles as a financial incentive to encourage its use and reduce carbon footprint.

Table 4. Equipment Costs and Financial Parameters.

Equipment costs (PL = 15.6%)	R$ 141,993.24
Equipment costs (PL = 23.5%)	R$ 217,359.67
O&M costs	1%/year
Inflation rate	5%/year
Energy price increase rate	8%/year
Panel degradation rate	0.8%/year
TOU Rate (peak hours 19 h–22 h)	2.63 R$/kWh
TOU Rate (off-peak hours)	0.31 R$/kWh

The Monte Carlo method was applied to evaluate the financial indicators and results are presented in Figure 15. In Case 1 (PL = 15.6%), the implementation of the system will yield an average NPV value of R$385,499, with minimum and maximum values of R$217,640 and R$516,970 respectively, and IRR has an average value of 22.3%. In Case 2 (PL = 23.5%), NPV has an average value of R$289,789, whose minimum and maximum values are R$121,930 and R$421,260 respectively, and IRR of 15.5% as an average value. Payback results are summarized on Table 5. In Case 1, payback time has an average value of 7 years, and in Case 2 an average value of 9 years. In both cases considered, NPV is always positive and IRR is greater than the minimum required rate of return of 7%, which confirms both projects are economically robust and attractive.

Table 5. Payback Statistical Results.

	PL_{PV} = 15.6%	PL_{PV} = 23.5%
Minimum	6 years	8 years
Mean	7 years	9 years
Max.	8 years	11 years

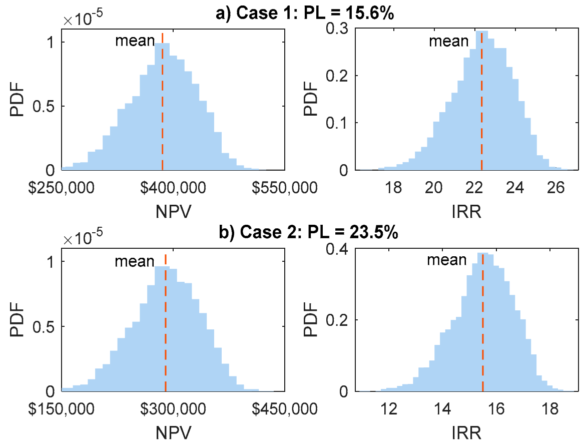


Figure 15. NPV and IRR. (**a**) Case 1: PL = 15.6%; (**b**) Case 2: PL = 23.5%.

4.3. Environmental Analysis

When analyzing vehicles environmental impact, it is important to perform its life cycle assessment (LCA), accounting from production to use, and ultimately its end of life recycling or disposal, as illustrated in Figure 16. These considerations are essential to assess the sustainability of such technologies. Regarding the using phase, PEVs have zero tailpipe carbon emission (tank-to-wheel contribution) since they run only on electricity. However, they may contribute indirectly with upstream emissions (well-to-tank contribution) depending on the electrical energy source used to charge vehicles. Countries that generate electricity using mostly renewable energies will have a much lower carbon footprint when charging PEVs, compared with countries that extract energy primarily from burning fossil fuels. Brazil has a low-carbon intensity (CI) grid electricity since its energy matrix is largely dominated by renewables sources, according Figure 17 [41]. In 2019, the average carbon intensity of Brazilian grid was 75 gCO_2/kWh [42]. As a comparison, UK grid carbon intensity was 241 gCO_2/kWh in 2019 [43].

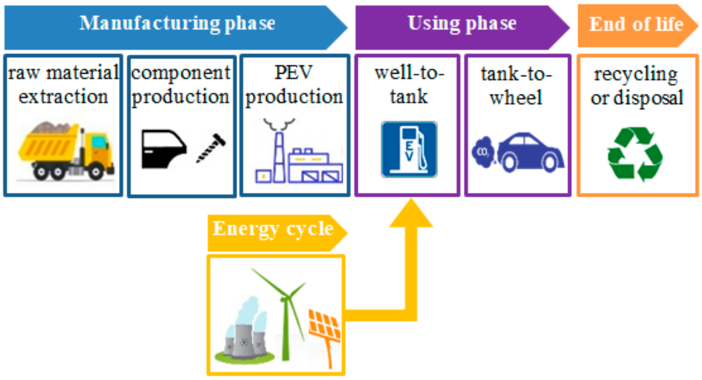


Figure 16. PEVs life cycle stages.

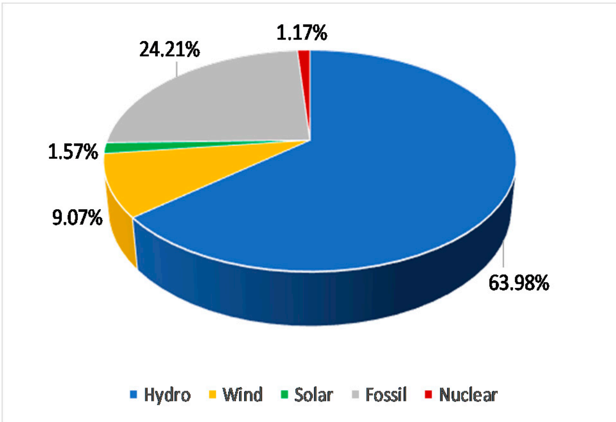


Figure 17. Brazilian energy matrix in 2019.

This section estimates carbon emissions avoided with the installation of 4 PEVs charging stations and a PV system at the central library parking lot. This analysis is limited to assess emission during the using phase. Manufacturing and end of life phases are not considered. The following assumptions are adopted:

- 15 PEVs are daily charged at the central library parking lot during weekdays;
- The PV emission factor is 21 gCO_2/kWh [44];
- The well-to-wheel (WTW) emission factor of internal combustion engine vehicles is 178 gCO_2 [45];

PEVs can be fully powered using electricity from grid or using electricity produced by PV system. In the latter case, it is important to consider situations where PV will not fully meet PEVs demand, which will be complemented with energy from grid. Both cases with different PV penetration levels are analyzed: Case 1: PL = 15.63% and Case 2: PL = 23.52%. The annual CO_2 emission produced by PEVs can be evaluated by Equation (16):

$$Em_{PEV}(gCO_2) = N_d.E_{PEV}^{grid}.F_{grid} + N_d.\ E_{PEV}^{PV}.F_{PV}, \quad (16)$$

where N_d refers to the number or days in the year excluding weekends, E_{PEV}^{grid} is the daily energy consumed from grid to charge PEVs in kWh, F_{grid} is the grid emission factor in gCO_2/kWh, E_{PEV}^{PV} is the daily energy consumed from PV to charge PEVs in kWh, and F_{PV} is the PV emission factor in gCO_2/kWh.

Emissions from internal combustion engine vehicles (ICEV) are estimated based on Equation (17), as a reference for comparison purposes:

$$Em_{ICEV}\ (gCO_2) = N_d.N_v.d.F_{ICEV}, \quad (17)$$

where N_v is the number of vehicles per day, d is the daily distance traveled, and F_{ICEV} is the carbon emission of combustion engine vehicles in gCO_2/km.

The probability density function of CO_2 emissions produced by PEVs and ICEV after the 10-year period are presented in Figure 18. Results show an average of 20.4 tonCO_2 produced when PEVs are charged entirely from grid. When PEVs are charged from PV generation and complemented from grid, an average value of 7.9 tonCO_2 is obtained in Case 1 and 7.1 tonCO_2 in Case 2, where PV generation is bigger. Comparing with the average value of 299.5 tonCO_2 produced when using only internal combustion engine vehicles, a substantial reduction of 93.2% is obtained when PEVs charged entirely from grid and 97.4% when PEVs are charged with local PV generation.

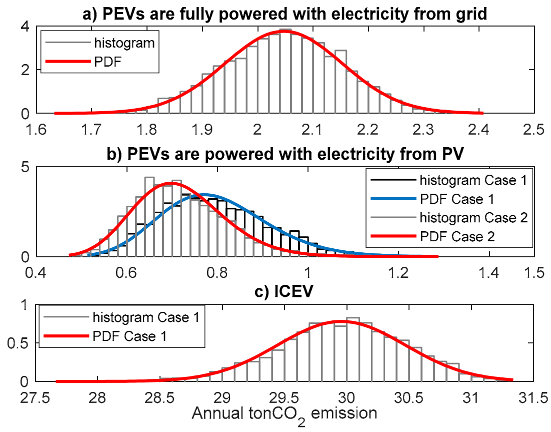


Figure 18. PDF of CO_2 emissions at year 10. (**a**) PEVs are fully powered with electricity from grid; (**b**) PEVs powered with electricity from PV and grid; (**c**) ICEV.

5. Conclusions

Electric vehicles are a viable option to reduce fossil fuel consumption and CO_2 emission in the road transportation sector. Given the high solar potential in Brazil and the early state of market development of electric vehicles, the integration of photovoltaic systems into PEVs charging infrastructure can be an attractive solution to the region, encouraging their use and reducing carbon dioxide emissions, with a cleaner energy matrix.

This paper proposes a probabilistic approach to investigate the impact occasioned by the integration of four PEV charging stations and a photovoltaic system in a university campus building located in Belem, Brazil. Monte Carlo method is applied to account the uncertainties effects on PEV demand, PV generation and building's electricity load. Simulations are based on historical load data collected by a local monitoring system installed in the building. Two different PV penetration levels are analyzed, and a study time horizon of 10 years is adopted. Analysis are conducted evaluating the effect on transformer load and voltage profile, carbon emissions avoided and the financial feasibility of the project. The achievement of this study led to the following conclusions:

- Even though distribution transformer has currently a low utilization factor of only 55% of its rated capacity, the connection of four Level 2 charging stations in the building parking lot will result in overloaded operation with a probability of occurrence of 77.9% in a future scenario of 9 years-ahead. This probability increases to 100% in year 10;
- The installation of a PV generation system with penetration level of 15.6% can reduce transformer overloading probability from 100% to 31.2%, and almost eliminate violations reducing overloading

probability to 8.2% when a penetration level of 23.5% is adopted. The overload duration is also reduced, from an average value of 4 h to 1 h;

- A substantial reduction of 93.2% tonCO_2 is obtained when PEVs are fully powered with electricity from grid, and 97.4% tonCO_2 when PEVs are powered with electricity from PV generation;
- In both photovoltaic systems projects (PL = 15.6% and 23.5%), NPV is always positive and IRR is greater than the minimum required rate of return of 7%, with payback periods varying from 6 years to 11 years, which confirms both projects are economically robust and attractive.

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