Optimum Design of On-Grid PV-BESS for Fast Electric Vehicle Charging Station in Brazil

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***Abstract*— Smart charging associating the synergy benefits of Photovoltaics (PV) systems and Battery Energy Storage Systems (BESS) can be used to minimize the negative impacts of Electric Vehicles (EVs) on the power distribution system. However, Electric Vehicle Charging Stations (EVCS) based on PV-BESS are more complex, and several topics must be analyzed, such as size and management. Concerning the sizing perspective, the present paper aims to provide an option to Brazilian charging infrastructure thought of an on-grid PV-BESS for fast EVCS. The proposed system comprises a modular solution that increases the PV power installed according to the previous load demand between 2020 and 2030. The power grid impact will be presented by comparing the required PV power installed to the consumed power from the grid by the charging station. The Homer Grid software is used to model, simulate, and optimize the EVCS.**

Keywords—Electric Vehicles, Charging Station, Battery Energy Storage System, Photovoltaic System

I. INTRODUCTION

Following the energetic transition tendency, electric mobility has expanded in several countries worldwide, such as Norway, Sweden, Netherland, United States, and Germany [1]. In Brazil, succeeding the vehicular electrification was recorded a 1,709% increase in Electric Vehicles (EVs) sales in the last four years. Moreover, the number of EVs circulating is crescent. In 2016 there were approximately 1,100 units of EVs circulating on Brazilian roads, against 42,269 units in 2020 [2].

Electric Vehicle Charging Stations (EVCS) are intrinsically related to the intensity of vehicle use. Therefore, the more EVs there are, the more charging stations will be used [3]. However, there are challenges associated with costs, impacts on the electricity grid, economic and technical feasibility, and load demand that limit the EVCS implementation. In Brazil, for example, besides the amount of EVs, there are just about 350 charging stations [2]. Furthermore, the stations are mainly located in the south and southeast regions due to the EVs concentration in these locals [4].

Relating the electricity grid impacts issue, EV penetration causes a new electricity demand that creates complexity in the conventional power system operation and planning [5]. Furthermore, the EV penetration into the distribution network brings novel challenges of power loss, stability, harmonic injection, phase and voltage unbalance [6]. Smart charging can be an opportunity to minimize the impacts of EV integration with the electricity grid, providing the most efficient usage of the available energy resources and dealing simultaneously with grid restrictions at each moment [5].

Researchers have proposed smart charging based on the synergy of EVs, Photovoltaics (PV) systems, and Battery Energy Storage Systems (BESS) [7]. Solar energy can reduce load demand peak as an alternative energy source, providing support for the electricity grid. The storage system can increase grid efficiency and reliability through optimizing power flows to the vehicle and supporting energy oscillation from PV generation [8].

However, despite the benefits, the integration of PV and storage systems for charging EVs can increase the complexity of EVCS. Topics of size, design, feasibility, management, control, and operation must be evaluated to develop the optimum technical-economic EVCS integrated with PV and BESS [9]. The number of studies concerning the mentioned topics varies according to the charging type, AC or DC. However, there are not considerable studies of fast DC charging stations based on PV and BESS [10].

Additionally, motivated by the lack of charging infrastructure in Brazilian territory and the benefits of EVs smart charging, this paper presents a design of an on-grid PV-BESS for fast DC charging in Campinas, Brazil. It is known that from the sizing perspective, several methodologies can be applied, depending on the goals required [9]. The criteria considered in this paper include costs, electricity tariff price, load demand, power grid utilization, area limitation, charging pattern, PV generation optimization, and recharge and discharge rate.

The aim is to provide an option to Brazilian charging infrastructure through a modular solution that increases the PV power installed according to the previous load demand from 2020 to 2030. The power grid utilization will be analyzed by comparing the PV power installed and the load demand increase. Therefore, will be presented the method utilized for calculating the energy demand of EVs. The proposed system will be formulated, optimized, and evaluated using the Homer Grid software.

II. METHODOLOGY

The components and premises considered for sizing the EVCS are described in this section. Fig. 1 presents the formulated EVCS composed of two EV fast chargers, PV system, BESS, and power grid. Succinctly, the energy source chosen to supply the load is defined from the levels of PV generation and the storage system's State of Charge (SoC). The objective is to optimize the PV generation and minimize the costs associated with the electricity consumption from the energy distribution network.

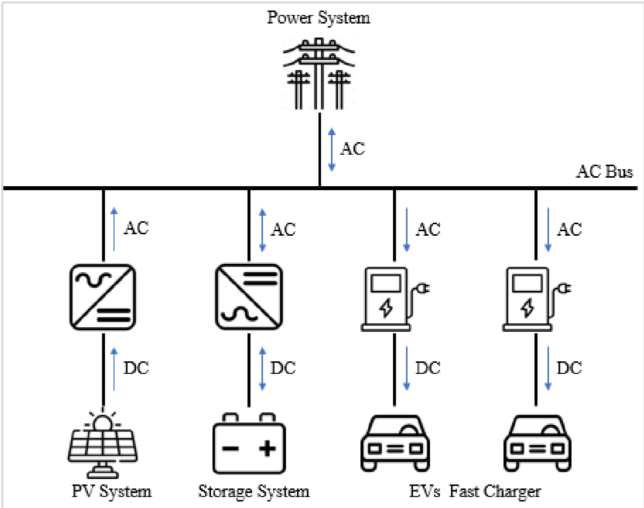

Fig. 1. EVCS topology

The energy generated by the PV system is used to charging EVs or BESS, depending on the EVs connection to the EVCS. If the BESS is fully recharged and there are not EVs for charging, the PV generation goes to the grid, producing credits for the energy compensation. The BESS is utilized for charging EVs whenever the PV generation is insufficient or unavailable, while the power grid is used when PV generation and BESS are not sufficient or available.

A. Homer Grid

The system is modeled, simulated, and optimized using the Homer Grid software. This software, developed by the National Renewable Energy Laboratory (NREL), allows the simulation of several system types based on the cost and energy resource availability. The program requires input information related to location for the analysis of resources, components, economic constraints, and control methods [11].

B. EV Demand

The energy demand for EVCS is calculated using the logistic growth model, which models the population growth and has been used to forecast new product sales. This model assumes that population growth is slowly in the beginning, then more rapidly, following more slowly after the inflection point and reaches the saturation limit [12]. The logistic growth function is:

$$I(t) = \frac{L}{1+\left(\frac{L}{I(0)}-1\right)e^{-kLt}} \tag{1}$$

With $I(t)$ = predict vehicles fleet at time t, L = saturation limit, $I(0)$ = vehicles fleet at the beginning (t=0), k= growth factor.

To find the logistic growth function parameters, the EVs number historical data of Campinas city from 2000 to 2019 are used, following the procedure indicated in [12]. Therefore, Fig. 2 shows the EV fleet growth curve in Campinas, comparing the historical data and the numbers obtained through logistic function.

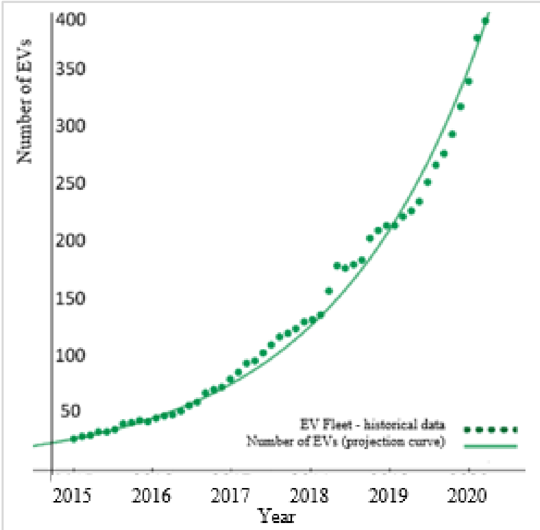

Fig. 2. EVs growth curve in Campinas

The EVs number estimate for Campinas is calculated considering the expected EVs fleet equal to the historical fleet growth. Thus, Equation (2) is used to meet the EVCS energy demand prediction, according to the EV number estimate for Campinas and the assumption that 5% of these EVs will be supplied for the proposed system.

$$C_{avg} = N_{EV} \times D_{m/day} \times \gamma_r \times C_{energ} \tag{2}$$

With C_{avg} = energy demand, N_{EV} = predict EVs number in Campinas, $D_{m/day}$ = average daily intensity of 54.1 km [4], γ_r = public charging stations use rate of 5% [4], C_{energ} = average energy consumed of 0.16111 kWh/km [13]. The average energy consumed is based on the average consumption of the more common EVs models in Brazil. The expected EVCS energy demand is shown in Table I.

TABLE I. FORECAST EVs NUMBER IN CAMPINAS

Year	EV demand (kWh/day)
2020	2.83
2021	5.26
2022	14.73
2023	19.32
2024	36.00
2025	65.81
2026	117.71
2027	180.55
2028	236.8
2029	283.34
2030	317.18

C. Load Profile

The load profile depends on different characteristics such as EV model, charging type, energy demand, and charging duration. The premises considered to obtain the charging station load profile are autonomy (300 km) and battery size (44 kWh) of the EV model Renault Zoe R100; average charging duration of 22 minutes; peak hours between 6 a.m. - 8 a.m. and 6 p.m. - 8 p.m.; two fast chargers (50 kW) and the energy demand calculated previously. Thus, for each energy demand calculated, one load profile is obtained.

D. PV System

The simulations are divided into two parts concerning the PV system. In the first one, there is not any limiting factor for the PV system installation. In the second part, the area is defined as a limiting factor. In both, the simulations assume the Campinas city geographic location and the PV module CS1U-400 features. Furthermore, the economic aspects considered are the initial cost of \$ 722.02/kWh and the O&M cost of 1%/year of CAPEX.

E. BESS

The storage system must supply the load when PV generation is not available or in periods of the day when the electricity tariff price is higher. Then, the BESS configuration is based on autonomy and system capacity for attending the load peak, which occurs when two EVs are charging simultaneously.

The peak load demand is 100 kW considering two EVs charging, and consequently, the BESS power is 100 kW. Besides that, the autonomy considered is two hours, which results in a BESS energy of 200 kWh. Thus, the BESS sized in simulations is 100 kW/200 kWh.

Furthermore, lead-carbon is the battery technology defined due to its benefits when integrated with EV and renewable technology [13]. The SoC variation assumed is between 20% and 100%, and the defined efficiency is 80%. The battery's lifetime is ten years. Related to economic aspects, the initial and the O&M costs are \$ 487.36/kWh and 1%/year of CAPEX, respectively. Finally, the battery replacement cost is \$ 108.30/kWh.

F. Power Grid

The electric distribution network is used for charging EVs whenever PV generation and BESS are not available or sufficient. To model the grid in Homer Grid, the input data used are the maximum power demand and energy tariff costs from Companhia Paulista de Força e Luz (CPFL). CPFL is a Brazilian Power System Company, which has an energy distribution concession area in Campinas.

The maximum power demand required value is 112.5 kW, established according to the load peak and the distribution transformer of the Company. The energy tariff costs considered are the values applied for consumers of subgroup A4, green rate.

These consumers are connected to medium voltage and have different tariffs during the day for electricity consumption and a single power demand tariff. The grid energy price in peak hours is \$ 0.29/kWh and in off-peak hours is \$ 0.08/kWh. The single power demand tariff is \$ 2.75/kW.

III. Results

The obtained results are discussed in this section. As mentioned, Homer Grid was used to perform simulations seeking to optimize the proposed system based on the established assumptions. Therefore, the optimum on-grid PV-BESS for fast DC charging for each estimated load demand will be presented. Fig. 3 shows the EVCS conceptual model performed on this paper.

Fig. 3. EVCS conceptual model

The simulations were divided into two parts. In the first part, there is not any limiting factor for the PV system. In the second one, the area for PV system installation is the limiting factor. It is expected that the larger the PV system is, the less the power grid will be used. Therefore, the objective is to analyze power grid utilization in different situations.

Table II presents the input parameters used and the expected output parameters. The load profile used in the simulations is composed exclusively of EVCS, and the EV demand was estimated by the logistic growth model. The BESS capacity is 100 kW/200 kWh. The power grid characteristics are based on maximum power demand and energy tariff costs from CPFL.

TABLE II. SUMMARY OF THE SIMULATED SCENARIO.

Input Parameters	Output Parameters
Load Profile	PV power
BESS Capacity	Grid power consumption
Power grid characteristics	Economic viability

A. Part I: without limiting factor

Initially, the area was not a limiting factor considered in the simulations. Therefore, one simulation for each estimated demand was performed to obtain the optimum PV system. Fig. 4 shows the PV system to meet the necessary PV power to supply the load of the EVCS.

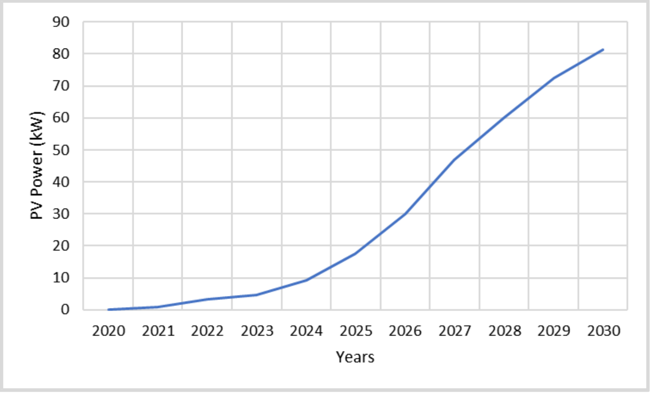

Fig. 4. PV power without limiting factor

It is observed that the increasing energy demand (Table I) requires a greater installed PV power to supply the load. The required PV power in 2030 is 81.60 kWp to meet the daily energy demand of 317.18 kWh. The smaller required installed PV power occurs in 2020 due to low demand.

The impacts on the power grid are analyzed by comparing the required PV power to the consumption from the grid. As mentioned, it is expected that the larger the PV system, the less the power grid is used. Fig. 5 shows the grid utilization to supply the load considering the PV system sized without limiting factor.

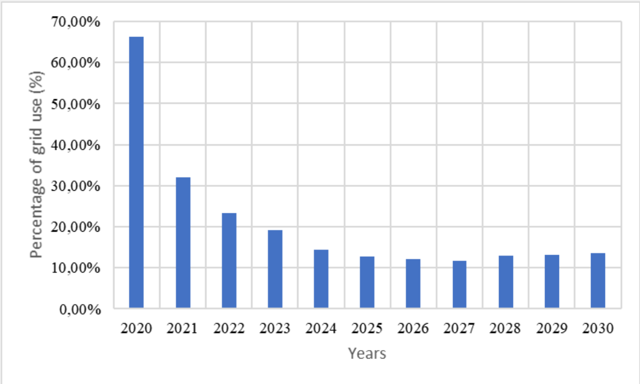

Fig. 5. Grid utilization without limiting factor

So, the increase of PV power reduces the power grid consumed as predicted. The year 2020 has the most considerable grid utilization (66.20%) due to the absence of the PV system. Besides that, the minimum grid utilization noticed is in 2027, when 11.70% of EVs charging used the grid (PV power of 47 kWp). The power consumed increases after 2027 due to the substantial load demand estimated between 2028 and 2030.

B. *Part II: with limiting factor*

The area of 340 m² was defined as a limiting factor to the PV system installation. Then, establishing a PV power value equivalent to a floor area of 340 m², the PV system was limited to 60 kWp in simulations. Fig. 6 shows the PV power necessary to meet the load demand for the performed charging station.

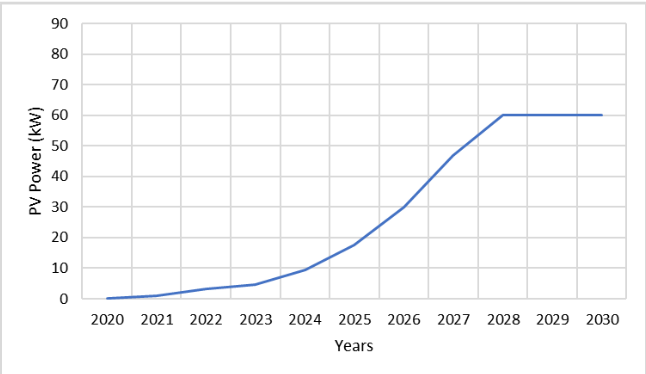

Fig. 6. PV power with limiting factor.

The PV power curve behavior is similar to the previous case when there was no limiting criterion. However, the PV system reaches its maximum power point allowed (60 kWp) in 2028 and remains for subsequent years. Consequently, it is expected an increase in the power consumed from the grid in these years. Fig. 7 presents the percentage of grid utilization.

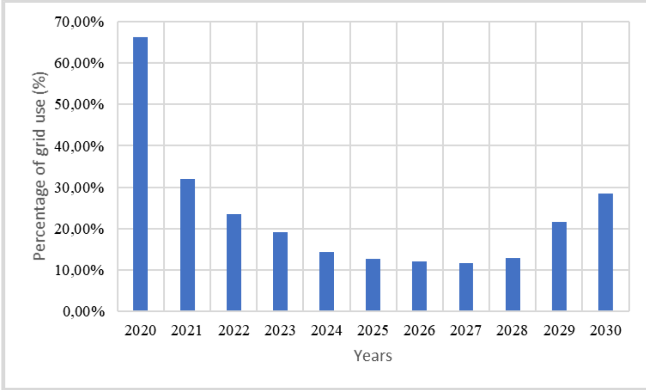

Fig. 7. Grid utilization with limiting factor

It is observed that limiting the PV system area limits the PV power installed on EVCS and, the need for power from the electric grid increases. Thus, even with the rising energy demand for EVCS over the years, the PV power does not follow it due to the fixed area. Consequently, the impact of EV charging in electric power systems has a growth tendency.

C. *Final Analysis*

To develop the optimum EVCS with the least impact on the grid, the results showed that area as a limiting factor requires more power from the grid than without limiting factor. Thereby, the greater the installed PV power, the less the electricity grid is used.

Fig. 8 shows a comparison between the estimated PV power and the electricity grid utilization in the scenario without any restrictive criteria. Fig. 9 shows the same comparison but with the restrictive area criteria. The power from the electric grid was about 50% greater with the area limitation.

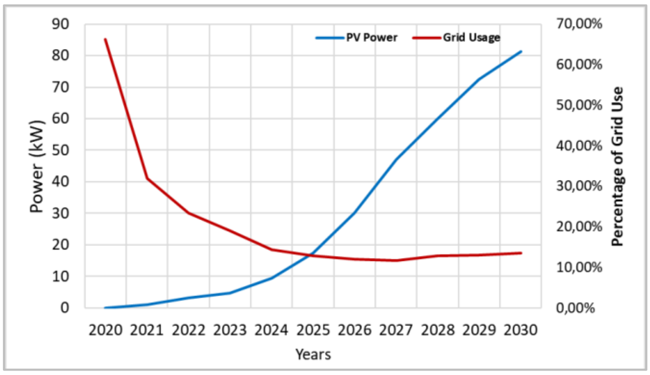

Fig. 8. Grid utilization without area limitation criteria

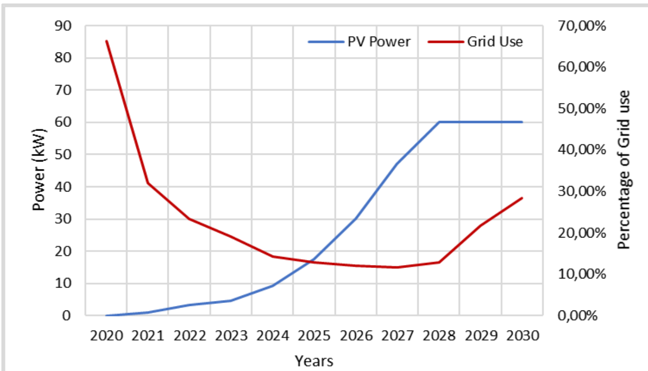

Fig. 9. Grid utilization with area limitation criteria

In addition, Table III presents the summary of the electrical parameters of the EVCS components in the case of lower network utilization, which occurred in 2027. Furthermore, the annual energy balance for this system is shown in Table IV.

TABLE III. ELECTRICAL SUMMARY OF THE SIMULATED SCENARIO.

Parameter	Value
Average Energy Consumption	180.55 kWh/day
Maximum Load Power	100 kW
BESS Capacity	200 kWh
BESS Maximum Power	100 kW
PV System	47 kWp

TABLE IV. ANNUAL ENERGY BALANCE OF THE SYSTEM.

Parameter	Value
Generated Energy – PV System	74,142 kWh/year
Supplied Energy – Power Grid	9,255 kWh/year
Consumed Energy - EVCS	66,482 kWh/year
Absorbed Energy - BESS	54,703 kWh/year
Dispatched Energy - BESS	43,824 kWh/year
Excess Energy	6,283 kWh/year

As shown in Table IV, most of the energy consumed by EVCS comes from the PV system. In this scenario, only 11.1% is supplied by the grid. The storage system is essential to achieve this result due to energy dispatch at opportune moments (during peak hours or when PV generation is insufficient to supply the load).

D. *Economic Results*

Finally, the economic viability of the proposed solution was also evaluated. This analysis considered aspects such as the operation characteristics, component lifetime, CAPEX, and O&M costs. The costs are based on the prices of the Brazilian Market and expressed in dollars in Table V.

TABLE V. ECONOMIC ASPECTS OF THE SYSTEM.

Parameter	Value
Internal Rate of Return (IRR)	14 %
Return of Investment (ROI)	10 %
Simple Payback	6.7 years
Initial Capital	$ 145,256.46
O&M	$ 5,221.38/year
Levelized Cost of Energy (LCOE)	$ 0.33/kWh

IV. CONCLUSION

This paper evaluates the optimum on-grid PV-BESS for fast EVCS in Campinas, Brazil. The EVs charging impacts on the power grid were analyzed by comparing the PV power installed to the grid utilization from 2020 to 2030. The load demand was calculated by the logistic growth model, and simulations were realized to meet the necessary PV power to supply it. It was noticed that the load demand impacts the PV power and the grid utilization. The increase of load demand required a greater installed PV power to supply the load, reducing the power grid utilization. Moreover, the results showed that setting the area as a limiting factor to the PV system installation requires more power from the grid than without a limiting factor.

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REFERENCES

[1] H. S. Das et al. “Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review”. Renewable and Sustainable Energy Reviews, 2020, 120, pp. 1–27.

[2] ABVE. "2020: the best year of electromobility in Brazil". “2020: o melhor ano da eletromobilidade no Brasil”, http://www.abve.org.br/2020-o-melhor-ano-da-eletromobilidade-no-brasil/, accessed 15 February 2021.

[3] FGV. “The electric vehicle market in Brazil: advances and lessons learned - O mercado de veículos elétricos no Brasil : os avanços e as lições aprendidas”. Boletim Energético, 2018, pp. 1–9.

[4] Promob-e. “Effective locations for electric vehicle charging stations in Brazil - Localizações eficazes para estações de recarga de veículos elétricos no Brasil”, http://www.promobe.com.br/library/localizacoes-eficazes-para-estacoes-de-recarga-de-veiculos-eletricos-no-brasil-relatorio-final/, accessed 20 January 2021.

[5] U. Datta, A. Kalam, and J. Shi. “Smart control of BESS in PV integrated EV charging station for reducing transformer overloading and providing battery-to-grid service”, *J. Energy Storage*, vol. 28, nº January, p. 101224, 2020.

[6] Y. Zou, J. Zhao, X. Gao, Y. Chen, and A. Tohidi. “Experimental results of electric vehicles effects on low voltage grids”, Journal of Cleaner Production, 2020, 255, pp. 120270.

[7] L. S. A. Grande, I. Yahyaoui, and S. A. Gómez. “Energetic, economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case study of Spain”, Sustainable cities and society, 2018, 37, pp. 519–529.

[8] R. Fachrizal et al. “Smart charging of electric vehicles considering photovoltaic power production and electricity consumption: A review”, eTransportation, 2020, 4, pp. 100056.

[9] C. T. Ma. “System planning of grid-connected electric vehicle charging stations and key technologies: A review”, Energies, 2019, 12, pp. 4201.

[10] Yang, L., and Hajo, R.. "Investigation of the potential to improve DC fast charging station economics by integrating photovoltaic power generation and/or local battery energy storage system." Energy, 2019, 167, pp. 246-259.

[11] Costa, T. S. and et al. “Optimum design of autonomous PV-diesel-battery hybrid systems: case study at Tapajós-Arapiuns extractive reserve in Brazil”, In: 2019 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America). IEEE, 2019. pp. 1-6.

[12] Rietmann, Nele, Beatrice Hügler, and Theo Lieven. "Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions", Journal of Cleaner Production, 2020, 261, pp. 121038.

[13] INMETRO, “Consumer Information - Informações ao Consumidor”, http://www.inmetro.gov.br/consumidor/tabelas_pbe_veicular.asp. accessed 15 October 2020.

[14] X. Hu, C. Zou, C. Zhang, e Y. Li, “Technological Developments in Batteries: A Survey of Principal Roles, Types, and Management Needs”, IEEE Power Energy Mag., vol. 15, no 5, p. 20–31, 2017, doi: 10.1109/MPE.2017.2708812.