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USING SOLAR ENERGY TO CHARGE ELECTRICAL VEHICLES, AN ANALYSIS OF THE BRAZILIAN NORTHEAST POTENTIAL

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Abstract. *This article analyzes the solar energy potential for each capital city of the northeast region of Brazil applied to the transportation sector. Taking into account the seasonal variability of irradiation levels, a photovoltaic charging station comprised of two solar modules is proposed to supply the energy demand of the projected northeastern battery electric vehicles (BEV) fleet. Even with conservative estimates, the present results indicate that the considered solar powered charging station in the cities of Aracaju, Recife, and João Pessoa, are capable of providing 100 % of the energy needed by one BEV. The only exceptions are São Luís and Fortaleza, which are capable of providing roughly 90% of the energy needed. Furthermore, and while the results obtained are promising, further real-life data is needed validate the proposed model.*

Keywords: *Renewable energy, Solar energy, Battery electric vehicles,*

1. INTRODUCTION

According to Ferraz et al.(2020), at the turn of the century, Brazil's heavy dependence on hydropower promoted the development of energy sources that were not climate dependent, resulting in the increase of non-renewable energy sources, such as thermoelectric power plants. However, an alternative to mitigate the seasonally of hydropower and to minimize the emissions caused by fossil fuel based plants is associated with the use solar and wind energy combined with hydro. As stated by (Ferraz et al.,2020), in the months when hydropower availability is low, solar and wind might be used, demonstrating great complementarity, and potential to diversify Brazil's energy mix.

As shown by the Brazilian Solar Energy Atlas (2017), Brazil has immense potential for solar energy production throughout the totality of its territory, with more solar irradiation reaching the southern region of the country than the most irradiated places in Germany, for example. As stated by ONS (2023), solar power generation in Brazil has been growing exponentially in recent years. Regarding centralized generation, for example, a total capacity of 892 MW was attained in January 2018, while in June 2023, Brazil has reached 8818 MW. Moreover, the growth of distributed generation followed a similar trend, with a total capacity increasing from 583 MW in January 2018 to 17066 MW in December 2022 (EPE, 2023), placing Brazil in 8th in the ranking of solar capacity installed (Irena, 2023).

As had been shown, solar energy production constitutes a significant share of Brazil's energy mix, though already predominantly renewable mix. However, as the economy grows, and therefore, so does the energy demand, the need for sustainable energy supply will be required. In that regard, it is fundamental to determine the impact of Battery Electrical Vehicles (BEV) as they will start penetrating the Brazilian market. Since BEV only consume electrical energy from the grid, they are only environmentally friendly if the energy added to the grid is also renewable. Therefore, supplying the energy demand of BEV with clean energy has become increasingly important aspect of the surging BEV market, which is projected to grow until 2032 (EPE, 2022).

Recently, several studies have studied different aspects of a BEV fleet. For instance, (Kulik, A. C, 2021) proposed similar study to the one presented here. In this case, the analysis was developed with experimental data of a BEV operating in the city of Curitiba (Brazil), however, instead of using a projection for the BEV fleet, the study considered that 15%, 30%, and 50% of the current city's fleet is replaced by BEV. Similarly, other studies focused on the use of BEV in the city of Campinas (Brazil). However, due to the low insertion of these vehicles in the market, each study proposed different models to estimate the impact of a future BEV fleet in the city. Noting that several studies strictly focused on one city at a time and used projections models sensitive to many variables, this article estimates the energy demand required by a projected BEV fleet that will penetrate the Brazilian market, using a projection made by the energy research company (EPE) and data from other governmental institutions, as well as related articles in the field.

Focusing on a large urban centers, this article also analyzes the potential of solar charging stations applied to BEV while considering each capital from the northeast region of Brazil (NRB), which would promote the use of solar photovoltaic modules to supply the projected demand. The relevance of this study lies in the projection of the impact on the electricity grid caused by the surge of BEV. It also helps to gauge how photovoltaic systems can help to mitigate the demand for electricity in different cities of the northeast. Based on the findings of this study, customers and governmental institutions have a clearer view of how many photovoltaic modules would be sufficient to supply electricity to the projected BEV fleet.

2. METHODOLOGY

This section presents the methodology adopted to estimate the future northeastern BEV fleet (NBEV) and the methods used to project its demand for electricity. Furthermore, the NRB is divided into four different regions according to each irradiation level. Also, it is proposed a PV charging station to supply the energy demanded by the future NBEV and the potential for solar energy production from the charging station is analyzed individually in each region.

2.1 Future NBEV Fleet

According to a report by EPE (EPE, 2022), Brazil's electrical fleet will reach roughly 200 thousand vehicles by 2032. As the present study focuses on the NRB, the projection from EPE for the national BEV must be scaled to that specific region. Assuming the same proportionality would take place with BEV as in normal vehicles, using data from a report made by the Ministry of Transportation (2022), the proportionality factor (X) is calculated in Eq. (1).

$$X=\frac{\text{Total Lightweight Vehicles in the NRB}}{\text{Total Lightweight Vehicles in Brazil}}= 0.13 \tag{1}$$

Therefore, assuming the same proportionality would take place for BEV, the yearly future NBEV fleet can be calculated by multiplying the projected battery electrical vehicle fleet (EVF) made by de EPE and the factor X, as follows in Eq. (2). Table 2 shows the results.

$$NBEV=EVF\cdot X \tag{2}$$

Table 1. Projected EVF and NBEV for each year.

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
EVF	17,929	28,179	40,196	54,034	69,731	88,489	110,711	136,853	167,437	203,062
NBEV	2,378	3,737	5,331	7,167	9,249	11,737	14,684	18,152	22,208	26,934

2.2 Energy demand

To project the yearly demand of the NBEV, a car model needs to be determined in advance. Considering that the BEV will be used in large urban centers as a non-polluting alternative for transportation inside the city, the compact Renault e-Kwid was selected in the present study. As indicated by the Brazilian Electric vehicle association (ABVE), in 2022, Renault sold 594 units, placing it in fourth in the list of most sold BEV in Brazil. The Renault e-Kwid was chosen due to its low cost when compared to other BEV (2° lowest) and its more practical and convenient design configuration with a 4-door setup.

Based on the Brazilian Vehicle Labeling Program (2023), the e-Kwid performance (N_e) is 0.44 MJ/Km. Considering that the BEV has limited autonomy, and as the infrastructure for BEV is still scarce in Brazil, this study will assume an annual mileage of 10,000 km. The yearly energy demand (E_y) was calculated as follows in Eq. (3).

$$E_y=NBEV \cdot N_e \cdot Kma \tag{3}$$

where E_y represents the yearly energy demand, NBEV is the northeastern battery electrical vehicle fleet, Ne is the efficiency of the model car and kma is the estimated annual mileage of the car.

2.3 Categorizing the NRB

According to Martins et al. (2007) Brazil has a considerable amount of solar irradiation and a low variability throughout the year when compared to other countries. Although the variability is low, most of the largest urban centers are located in coastal regions where the climate can be considerably different from the countryside. However, a recent work by (Lima F et al., 2019) studied the effect of time (i.e. temporal) on the solar energy availability for each location of NRB. Moreover, the data was grouped by regions with similar irradiation values; the reader is directed to Lima F et al. (2019) for a detailed description of the data. Region 1 encompasses the cities of Salvador, Aracaju, Recife, and João Pessoa, Region 2 encompasses the city of Natal, Region 3 Teresina and Region 4 São Luís and Fortaleza.

Table 2 shows the monthly mean global irradiation by region, using data available in Lima F et al. (2019). Based on the data displayed by Table 2, it becomes clear that the irradiation value for each region and month varies significantly, due to different climates, especially for the capital cities, which, excluding Teresina, are located in the coastal area. As an example, in January alone region 4 registered only about 70% of the irradiation levels obtained in region 2, demonstrating that only gathering one average yearly value for the entire NRB is not ideal. Region 1 and Region 2 follow the same pattern with region 2 having a slightly higher value in average, with the highest values occurring in the summer. Region 3 and region 4 reach peak irradiation values throughout August and October, while leveling down in the other months.

Table 2. Monthly total mean global Irradiation (MJ/m^2) by region (Lima F et al., 2019).

Region	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	679	657	657	569	481	449	471	537	613	657	670	679
2	712	701	690	635	590	547	569	657	722	733	711	700
3	602	591	602	580	558	569	602	668	711	689	657	624
4	503	503	514	492	481	525	547	602	613	591	547	525

2.4 PV Charging station for BEV

A BEV is only truly environmentally friendly as long as its energy source is sustainable. Bearing that in mind, this study proposes a PV charging station to supply the demand projected by the upcoming NBEV. First, it is needed to estimate the monthly demand of one BE. In this case, a similar approach as in section 2.2 will be used. With the efficiency Ne in MJ per km of the model car and an average monthly commuting distance of 833.333 km, the monthly energy demand is estimated by Eq. (4).

$$E_m = 1.15 \cdot 833.333 \cdot Ne \tag{4}$$

where E_m represents the monthly energy demand of the model car, Ne is the efficiency of the car model in MJ/km and 833.33 km is the monthly commuting distance. In addition, a correcting value of 15% will be used on the energy demand as both (Mattes P et al., 2017) and (Kostopoulos E et al., 2018) noticed with experimental data that the energy necessary to charge the BEV was 15% higher than the actual battery capacity of the vehicle, mostly due to heat losses in the charging system.

The charging station is comprised of two HiKu7 PV modules. According to the (Hiku7 datasheet, 2023) provided by the company Canadian Solar, each module is 2.384 meters wide and 1.303 meters long, has a nominal peak power of 650 W and a conversion efficiency (N_c) of about 0.2 under standard test conditions (STC). This totals an area of 6.212 m^2 and a nominal peak power (W_p) of 1300 W.

As the real-world performance of the solar module differs significantly from the STC, a performance ratio PR will be adopted to most accurately depict reality. The PR is a measure of the actual energy output of the solar module against its theoretical output in ideal conditions (SMA Solar Technology, 2023). Eq. (5) depicts how the PR of a solar module or solar plant can be calculated.

$$PR = \frac{\text{Energy Output Reading}}{\text{Theoretical Energy output}} \tag{5}$$

Eq. (5) tell us that the PR is not dependent on location, as the theoretical energy output already takes into account the solar irradiation values from the specific location of the solar plant or module

(Kulik, A. C, 2021) measured an average PR of 68.04% during a 24-month time frame in the city of Curitiba with polycrystalline solar modules. (Khalid A.M, 2016) states a value of 81% for monocrystalline and 78.2% for polycrystalline solar modules in the Malaysian climate.

The PR of a solar module has an inverse relationship with the temperature of the module. Consequently, during the summer, the PR declines due to the higher levels of irradiation, causing the temperature of the module to rise and its efficiency to decline. Considering that NRB has higher levels of irradiation than the examples cited above, a conservative PR of 65% will be adopted.

Moreover, as used by both (Ramirez I, 2017) and (Mattes et al., 2017), an efficiency for the inverter (N_{inv}) of 0.9 will be accounted. A global efficiency (N_{glo}) for the system can be defined according to Eq. (6).

$$N_{glo} = N_c \cdot N_{inv} \tag{6}$$

The monthly energy produced from the charging station (E_{cs}) will vary depending on which region and month. This variable is calculated by the following expression, Eq. (7).

$$E_{cs}=I_r \cdot A \cdot N_{glo} \cdot PR \tag{7}$$

where I_r is the irradiation in the location and month of the year, A is the area of the two modules, N_{glo} is the global efficiency of the system and PR is the factor to correct from the theoretical to the real energy output.

For comparison, it will be estimated in Eq. (8) the area needed, in solar modules, to power half of the current fleet of lightweight vehicles in the NRB (NLEV), if they were to be BEV. Results will be discussed in the following section.

$$\text{Total area}=\frac{NLEV \cdot Kma \cdot Ne \cdot 0.5}{I_{rm} \cdot Nglo \cdot PR \cdot 10^6} = 24 \text{ Km}^2 \tag{8}$$

where I_{rm} is the average annual mean global irradiation in all four regions, 0.5 is to adjust to half of the fleet and the 10^6 in the denominator is to transform from m^2 to km^2.

3. RESULTS AND DISCUSSION

Based on the proposed methodology, it was possible to estimate the number of BEV in the NRB and the energy demand required to charge these vehicles, which are depicted in Figure 1. As can be seen, by 2032 the number of BEV in the NRB is estimated to reach 26,934 units, requiring 33 GWh. Figure 1 was made applying Eq. (3) to the corresponding NBEV at each year, according to Table 1.

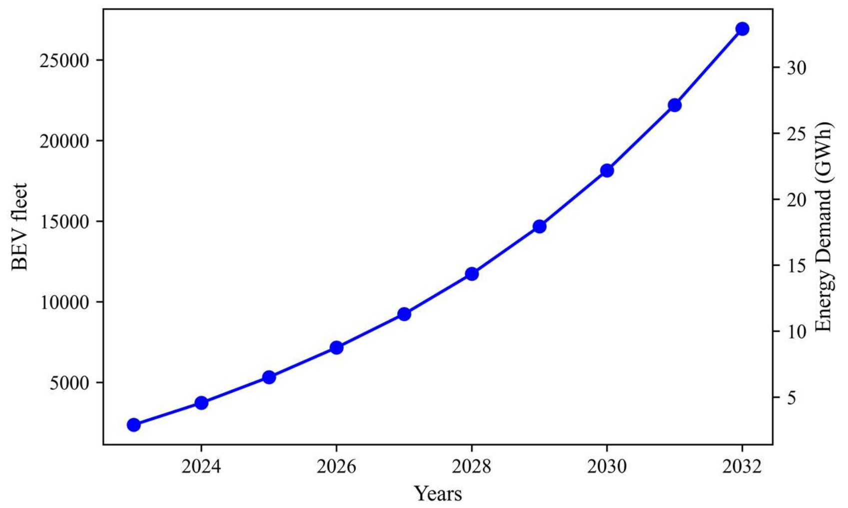

Figure 1. Energy demand caused by the NBEV in the NRB.

For comparison, the hydropower plant Xingó, located in the states of Alagoas and Sergipe, as stated by (Eletrobras Chesf, 2023) has a capacity installed of 3,162 MW (placing 7th) and produced 15,272 GWh in 2022 according to (ONS, 2023), representing only 0.21% of the total energy generated by Xingó in 2022.

The electricity generated by the charging stations is depicted in Figure 2 in terms of the perceptual fraction between the energy produced by the charging station (Ecs) and the monthly demand of the BEV (Em) for each region. Ecs was calculated by considering irradiation (Ir) values from Table 2 into Eq. (7), with the irradiation varying with region and month of the year.

Figure 2 shows that the monthly energy demand is not met in all months of the year. It can be observed that in the winter months of May, June, and July all four regions do not reach 100% of the demand, with exceptions of Region 2 in May and Region 3 in July. Moreover, the lowest value obtained was about 77% in Region 1 during June.

Between the months of September and March, regions 1, 2 and 3 produced more than 100%, with region 2 constantly peaking values of over 120%. These results indicates that during spring and summer, the station is recording net surplus, injecting electricity in the grid, allowing the station to ease down demand during the period with peak electricity consumption.

Region 4 was the only region that could not supply the yearly energy demand, reaching 91%, which is still a high value. Regions 1, 2 3 reached 101%, 112% and 105% of the yearly energy demand respectively.

Regions 2 and 3 demonstrate the best outcome, with the lowest recorded values of 94% and 96% and maximum values of 126% and 122%. Region 1 exhibits the biggest variability of all four regions while still maintaining a net surplus during September through March, with max and minimum values of 117% in January and 77% in June. Region 4 was the only region that did not attain great results while having the lowest variability of all four.

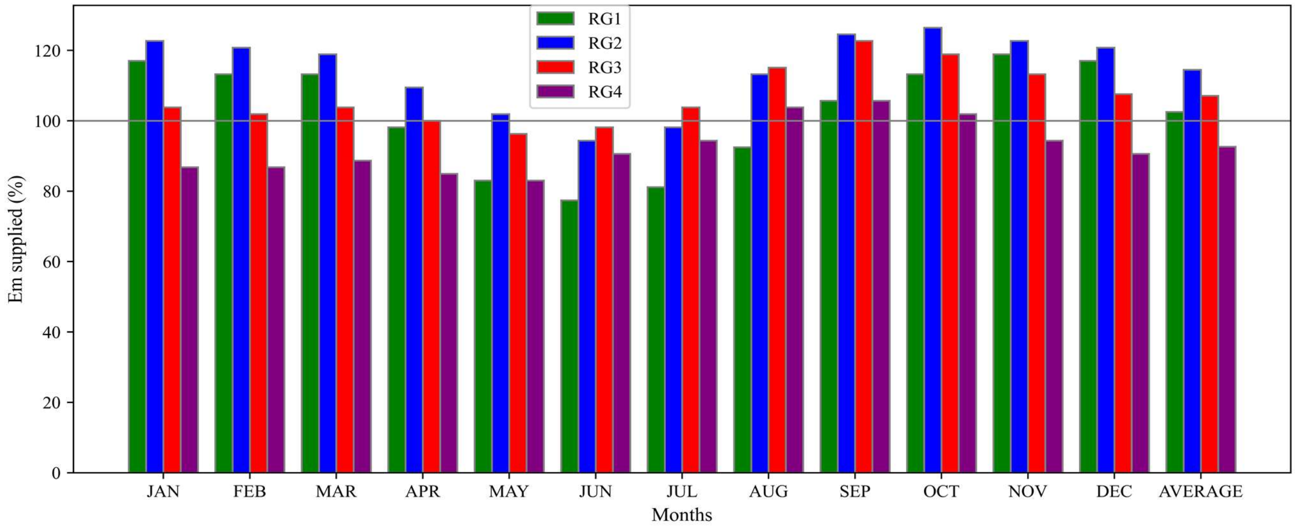

Figure 2. Bar plot of the percentage of energy demand met by PV charging station, by region, by month.

In order to determine the total number of charging stations needed, an average I_r value will have to be evaluated, as the proportion of NBEV in each region cannot be accurately determined. A simple arithmetic average was used to obtain the annual average in each region, then the same process was used to obtain the average annual mean global irradiation (I_{ave}) between all four regions. The irradiation data required to calculate the mean values were presented in the previous section. Therefore, the number of PV stations (NS) needed for each year can be obtained in Eq. (9).

$$\text{Number of PV stations} = \frac{Ey}{I_{ave} \cdot A \cdot N_{glo} \cdot PR} \quad (9)$$

where I_{ave} is the recently defined average annual mean global irradiation in all four regions, A is the total surface area of the two PV modules, N_{glo} is the global efficiency of the system and PR is performance ratio.

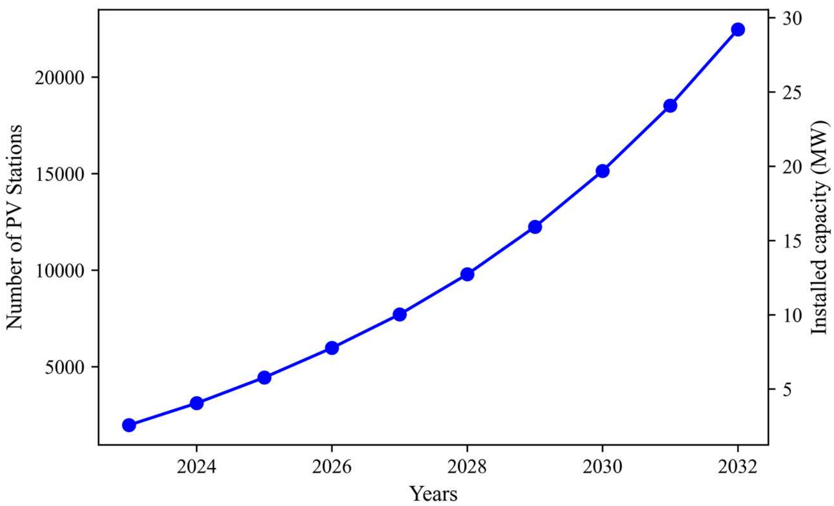

Figure 3. Number of PV Stations and capacity installed required to supply the NBEV.

Figure 3 was made by applying Eq. (9) to the yearly energy demand (Ey) each year. It depicts the estimated additional PV installed capacity to charge the NBEV based on the numbers of PV stations. The capacity installed was calculated by multiplying NS and Wp. The proposed method is only feasible given that the projection for BEV in Brazil does not constitute a large percentage of the national fleet. Eq. (8) shows that approximately 24 km^2 of solar panels are needed to supply half of the NLEV, if they were to be BEV. The result from Eq. (8) indicates that its feasibility is questionable, given the fact that solar modules are still relativity expensive and that 24 km^2 of land dedicated only to solar modules might not be practical. Figure 3 also states that almost 30 MW of capacity installed would have to be added until 2032. (EPE, 2023) asserts that in the same time frame, 27,000 MW of distributed generation alone will be added in the electricity mix. Therefore, the added capacity installed predicted is in line with the prediction from the EPE, further validating its feasibility.

In the beginning of the section it was commented how the energy demand from the NBEV in 2032 would only represent 0.21% of the total energy produced by Xingó in 2022 due to the reduced number of BEV projected to enter the market until 2032. The relativity low energy demand is due to the low numbers of electrical vehicles projected to enter the market until 2032. In that sense, Figure 4 represents the energy demanded by the NBEV assuming it will continue to grow exponentially at a rate of 20% a year until 2050. The energy demand was calculated according to Eq (3). In 2050 the energy demand would be equivalent to 4.3 times the energy produced by Xingó in 2022. For instance, Itaipu yielded 52,521 GWh in the same time frame (ONS, 2023) demonstrating the if the NBEV continues to grow at the same rate after 2032, the energy demand would cause a significant impact on grid, requiring careful planning.

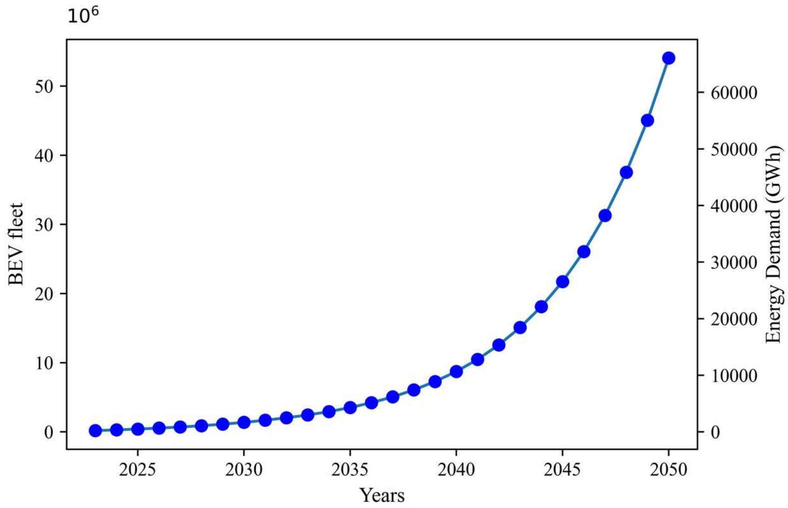

Figure 4. NBEV and Energy demand until 2050.

4. CONCLUSIONS

This article analyzed the solar energy potential of each major city center of the NRB and applied it to the transportation sector, most specifically the BEV sector. Results show that a PV stations comprised of two solar modules are capable of supplying the energy of one BEV in almost all capitals cities of the NRB, failing to achieve yearly net surplus only in the cities of São Luiz and Fortaleza. Furthermore, it is shown that the additional solar energy capacity installed needed to supply the NBEV aligns with the prediction from EPE. The results could also be used for decision-making purposes aiding BEV users, as well as the public and private sectors on developing future energy strategies and projects for including BEV in the Brazilian fleet.

The data and methods utilized can be applied to other countries, which fall into the same category of emerging BEV markets and thriving solar energy industries, providing useful data to support future energy related projects. Although results are optimistic, experimental data is needed to validate the results found in this study as most parameters used in the equations depend on a series of parameters, such as solar irradiation, which can vary significantly from year to year.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

de Andrade Santos, J.A.F., de Jong, P., da Costa, C.A. and Torres, E.A., 2020. “Combining wind and solar energy sources: Potential for hybrid power generation in brazil”. Utilities Policy, Vol. 67.

de Lima, L.C., de Araújo Ferreira, L. and de Lima Morais, F.H.B., 2017. “Performance analysis of a grid connected

photovoltaic system in northeastern brazil". Energy for Sustainable Development, Vol. 37.
ELETROBRAS, 2022. "MLA works cited: Electronic sources (web publications)". ://www.chesf.com.br/SistemaChesf/Pages/SistemaGeracao/Xingo.aspx Accessed 05 June 2023.
EPE, 2022a. "Light vehicles energy demand: 2023 - 2032 (in portuguese)". https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-331/topico-656/NT-EPE-DPG-SDB-2022-09_Demanda_Ve%C3%ADculos_Leves_2023-2032.pdf. Accessed 05, June 2023.
EPE, 2022b. "Studies of the ten-year energy expansion plan 2032, distributed micro and mini generation batteries (in portuguese)". https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao689/topico-640/CadernoMMGDBaterias.pdf.Accessed27June2023.
EPE, 2023. "Studies of the ten-year energy expansion plan 2032, distributed micro and mini generation batteries (in portuguese)". https://dashboard.epe.gov.br/apps/pdgd. Accessed 14 June 2023.
INMETRO, 2023. "Brazilian vehicle labeling program - pbev." https://www.gov.br/inmetro/pt-br/assuntos/avaliacao-daconformidade/programa-brasileiro-de-etiquetagem/tabelas-de-eficiencia-energetica/veiculos-automotivos-pbe-veicular. Accessed 05 June 2023.
IRENA, 2023. "Country rankings". https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/CountryRankings. Accessed 14 June 2023.
Emanuel Jordão, 2022. "Brazilian electric vehicle association (in portuguese)." http://www.abve.org.br/em-ano-de-recordes-veiculos-Accessed 05 June 2023.
Khalid, A.M., Mitra, I., Warmuth, W. and Schacht, V., 2016. "Performance ratio – crucial parameter for grid connected pv plants". Renewable and Sustainable Energy Reviews, Vol. 65.
Kostopoulos, E., Spyropoulos, G., Christopoulos, K. and Kaldellis, J.K., 2018. "Solar energy contribution to an electric vehicle needs on the basis of long-term measurements". Elsevier B.V., Vol. 10.
Martins, F.R., Pereira, E.B. and Abreu, S.L., 2007. "Satellite-derived solar resource maps for brazil under swera project". Solar Energy, Vol. 81.
Mattes, P., Ch, P., Oliveira, A.K.V.D. and Rüther, R., 2018. "Performance of an electric bus, powered by solar energy". of Transportation, M., 2022. "Vehicle fleet - 2022 (in portuguese)". https://www.gov.br/transportes/pt-br/ptbr/assuntos/transito/conteudo-Senatran/frota-de-veiculos-2022. Accessed 05 June 2023.
ONS, 2023. "Energy generation (in portuguese)." https://www.ons.org.br/Paginas/resultados-da-operacao/historico-daoperacao/evolucaocapacidadeinstalada.aspx. Accessed 27, June 2023.
Pereira, E.B., Martins, F.R., Gonçalves, A.R., Costa, R.S., Lima, F.J.L.d., Rüther, R., Abreu, S.L.d., Tiepolo, G.M., Pereira, S.V. and Souza, J.G.d., 2017. Atlas brasileiro de energia solar. INPE.
Ramirez, I.L. (2017) Operating correction factor of PV system. Faculty of engineering and sustainable development. University of Gavle.
SMA Solar Technology AG, Performance ratio, Quality factor for the PV plant. Retrieved June 26, 2023, from https://files.sma.de/downloads/Perfratio-TI-en-11.pdf

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