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Impact on the Distribution Grid Due to the Introduction of Electric Vehicles on Fernando de Noronha Island (Brazil)

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HIGHLIGHTS

- Evaluation of the impacts of electric vehicles penetration on distribution grids.
- Power flow simulations on GridLab-D software considering the distribution grid with electric vehicles charging stations and a carport.
- Analysis of the real distribution grid of Fernando de Noronha Island.

Abstract: Increasing global temperatures over the past years have become a worry. To mitigate this, countries have set out to decrease their greenhouse gas emissions soon. A major contributor to these emissions has been the transport sector. Electric mobility has appeared as an opportunity to decarbonize this sector. With this in mind, Fernando de Noronha Island, a UNESCO World Heritage Site, has determined to ban all fossil fuel vehicles by 2030. Understanding the impact electric vehicles can have on the island's distribution grid is fundamental to achieving this goal. To determine these impacts, electrical vehicle chargers were added to the model of the island's power system in GridLad-D. Apart from these chargers, the impact of adding an extra carport charger fitted with solar panels was also determined. In total, six different charging scenarios were simulated, with each varying the period in which vehicle charging was allowed to take place. The impacts were determined for the day, afternoon, and night charging, with and without the presence of a carport. The parameters measured include system power demand, voltage, and total losses. From the results, it was possible to determine the charging strategy that causes the least and most impact on the system's distribution grid.

Keywords: Electric Vehicles; Distribution Grids; GRIDLAB-D; Carport; Charging Strategies.

INTRODUCTION

Global CO2 emissions have been a cause of concern for governments worldwide. Global temperature data document a warming trend since the mid-1970s. The warmest years globally have all occurred since 1998, with the hottest ever recorded year being 2016 [1]. Reduction of greenhouse gas (GHG) emissions is crucial to keeping the planet's temperature at acceptable levels.

In Brazil, vehicles were responsible for the emission of 31 million tons of CO2eq (CO2, CH4, and N2O) during 2018, being 70% emitted by cars and motorcycles, and 30% by buses, used mainly in public transport [2].

An option to reduce these levels of greenhouse gas (GHG) emissions is the substitution of internal combustion engine vehicles (ICEs) by electric vehicles (EVs), including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). In 2019, sales of electric cars topped 2.1 million globally, reaching a total stock of 7.2 million electric vehicles, about 1% of the total global car stock, avoiding the consumption of almost 0.6 million barrels of oil products per day [3].

Different European countries had already set targets to ban the acquisition and usage of ICEs. Although Brazil has not yet set a target to eliminate vehicles that burn fossil fuels from the market, there are some policies that benefit the introduction of EVs into the fleet. The policy that stands out most is the ROTA 2030, which establishes energy efficiency goals for the automotive sector, also including tax reductions for hybrid vehicles, as well as for more energy-efficient cars [4]. In a more aggressive approach, the entry of internal combustion engine vehicles has been prohibited on the island of Fernando de Noronha. Through the Pernambuco state law Nº 16.810, published in January 2020, from the beginning of August 2022, no new ICE vehicles will be allowed to enter the island, and from 2030 onwards, all ICEs are to be banned from circulation.

As the growth in demand for the electrical vehicle is inevitable, the electrical grid must be ready to accommodate this new load. In this way, various studies have shown that an excessive amount of EVs charging at the same time on a local distribution grid can cause problems such as voltage drops, overloading of transformers, and an increase in peak demand.

The impact that electric vehicles have on different parts of the power system was studied in [5]–[8].

Salah and coauthors [5] defined the impact of inserting EV into the Swiss power grid, mainly focusing on distribution substations. It found out that EVs could reach a penetration of 50% by 2040 before any substations were overloaded. At 100% penetration, the number of overloaded substations recaches six. When dynamic pricing is adopted, a substation overloads with a lower level of penetration.

Romo and Micheloud [6] focused on the impact of EVs charging on the local distribution grid, based in Austin, Texas. For 100 houses with EVs, the main feeder was found to be lightly loaded. Since house loads are single-phase, there is a current unbalance for each of the phases that creates a voltage unbalance in the feeder. Simulation results indicate that coordinated charging for electric vehicles reduces the load at peak time. The addition of PV panels can also reduce transformer loading during the day.

Dogan and coauthors [7] compared different charging strategies' impact on the power grid peak demand, utilizing GridLab-D software to model and simulate the distribution grid. With no charging strategy adopted, a penetration level of 30% can already cause problems for the distribution grid. With the adoption of specific charging times, higher penetration levels were reached before stressing the grid, even when using high power vehicle chargers, with the best strategy begin charging solely at night.

Marmaras, Xydas, and Cipcigan [8] modeled and simulated the EV and its interactions in both road transport and electric power systems. Two types of EV owners were modeled, with different behavioral profiles, the aware and unaware agents. The unaware agent will seek to recharge the vehicle frequently, while the aware agent will only recharge when needed. The results indicate that unaware EV agents start charging when they return home, around 17:30–18:00. Their charging demand coincides with the evening peak of the residential demand, increasing in peak demand. The high charging demand stressed the distribution network infrastructure, causing increased line losses and voltage drops. The aware EV agents, on the other hand, places their charging during the off-peak hours, between 22:00 and 06:00, resulting in a valley-fill effect on the demand profile.

Other approaches related to EV impacts on grid integration are presented in articles [9-10].

The work developed in [9] presents the main impacts of Plug-in EV integration, considering the analysis of the IEEE 38 buses distribution system. For the analysis, the authors consider smart systems as grid-to-vehicle and vehicle-to-grid applications, to reduce the impacts of congestion load management due to EV charging.

Datta and Das [10] present the energy management study considering the integration of Plug-in EVs in a distribution system with multiple microgrids, with distributed generation and storage systems. The authors proposed an optimization strategy to minimize the microgrids' costs, considering the operation of dispatchable and non-dispatchable generation, energy storage systems, flexible loads, as well as the stochastic behavior of the EVs.

The main objective of the present study is to evaluate the introduction of electric vehicles in a real distribution system, being chosen for the study the power grid of Fernando de Noronha Island, which consists of an isolated system, fed by diesel generators and solar systems. To accomplish this goal this study proposes the evaluation of the Fernando de Noronha power grid operation *ex-ante* and *ex-post* the placement of EV chargers, being considered different operational scenarios. To define the number and location of the chargers, the current fleet characteristics were evaluated. Aiming to analyze the power grid behavior, a grid modeling at GridLAB-D was used, being added the EV chargers and a carport system. From the power flow simulations distribution grid parameters as power losses and voltages were evaluated and compared across the proposed scenarios.

This paper is organized with the following sections. Electric Vehicles and Power Grids, brings an overview of the current technology of electric vehicles and chargers are presented, along with the main impacts on power grids. Case of Study details the power system present at Fernando de Noronha Island and the simulation tools used. The Methodology describes the charging scenarios simulated and the analysis methods. Results present the main results obtained from these simulations for each scenario and a comparison between them. Finally, the Conclusion summarizes the results obtained and brings forth the final considerations and proposals of future works on this topic.

Electric Vehicles and Power Grids

Electric Vehicles Overview

Electric vehicles can be separated into two main groups, hybrid electric vehicles (HEVs) and all-electric vehicles (AEVs). AEVs are equipped with only electric motors powered by electrical sources [11], while HEVs use an internal combustion engine alongside an electric motor. AEVs can be further classified into Battery EVs (BEVs) and Fuel Cell EVs (FCEVs). HEVs can correspond to vehicles that have an electric motor and a small storage system that is charged by the regeneration of power from a combustion engine system, do not present a plug to be connected to the electricity grid. A plug-in hybrid EV (PHEV) is one type of HEVs with an option to recharge its battery from the grid [11]. For this paper, BEVs and PHEVs will be addressed together as EVs.

Lithium-Ion (Li-Ion) batteries are the most common battery type in modern electric vehicles, mainly due to their high energy density and increased power per mass battery unit, allowing the development of batteries with reduced weight and dimensions at competitive prices [12]. A Li-Ion battery can be modeled in terms of its terminal voltage, open-circuit voltage, internal resistance, discharge current, and state-of-charge, being these characteristics used in the discharge and charge modeling [13]. A typical discharge curve can be seen in Figure 1.**Erro! Fonte de referência não encontrada.**

It can be noted that at the start of the discharging process, exponential behavior is observed. Shortly after, a linear relationship between voltage and battery capacity is established, defined as the nominal area. After nominal capacity is exceeded, the voltage rapidly falls to zero, stating the battery is fully discharged.

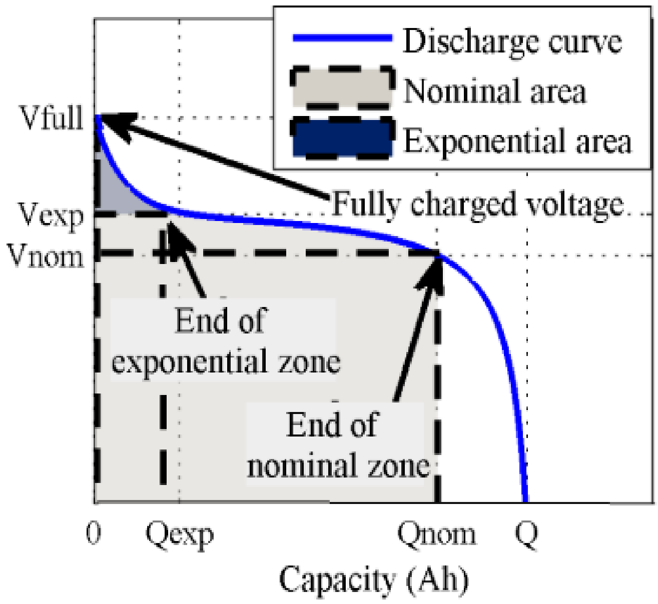

Figure 1. Typical discharge curve for li-ion battery.

The power required by the vehicle is proportional to its speed. Therefore, higher speeds require the battery systems to provide more power. Assuming the voltage is constant during the nominal area of discharging, the current output of the battery pack will increase to provide the extra power, thus having a faster discharge time. Assuming the vehicle travels at a constant speed, the energy consumed per kilometer can be defined as *E*, given by (1), being *Q* the energy consumed from the battery to reach a certain distance d given in kilometers.

$$E = \frac{Q_{consumed}}{d} \quad (1)$$

The condition of the battery is given by its state of charge (SOC), which can be defined as shown in (2), where $SOC_0$is the state of charge at the beginning of the trip, d the distance of the trip, and $Q_{nom}$the nominal capacity of the battery [14].

$$SOC = SOC_0 - \frac{d * E}{Q_{nom}} \quad (2)$$

Once the SOC reaches a low enough point, BEVs and PHEVs can recharge at appropriate charging stations, these being either private or public. EV charging systems can be broadly classified as conductive and inductive charging systems. Conductive charging systems are well established and more common in use than inductive systems [15] being this kind of system is usually installed in homes, workplaces, and public charging points since requires small charger stations. As inductive charging does not represent a great market share of total chargers, in this way only conductive chargers will be detailed below.

The Society of Automotive Engineers (SAE) and Electric Power Research Institute (EPRI) have categorized EV charging levels as AC Level-1, AC Level-2, and DC fast charging or Level-3 charging, along with the subsequent functionality requirements and safety systems [15]. Level 1 charging utilizes a 120 V AC outlet, capable of supplying power in the range of 1.4 to 1.9 kW, taking 8 to 16 hours for a full recharge of the vehicle, depending on the battery capacity and type. Level 2 charging uses a single phase 240 V AC outlet, having a current-carrying capacity of 40 A for private systems and a three-phase 400 V AC connection having a current-carrying capacity of 80 A for public installations, capable of delivering power at 7.7 to 25.6 kW, completing a full charge in 4 to 8 hours. Level 3 charging consists of an AC to DC converter, supplied by a three-phase circuit ranging from 208 to 600 V, with a carrying capacity of up to 200 A, offering up to 80% of the batteries capacity in about 10 to 15 minutes, depending on EV battery type and size. Because of the considerable amount of time required by a level 1 or 2 chargers to fully recharge a modern EV, most charging is done overnight, when the vehicle is not in use and electricity prices are lower. Figure 2 presents the charging start time and duration for individual EVs throughout a year, for a distribution grid located in the USA, according to Gerossier, Girard and Kariniotakis [16].

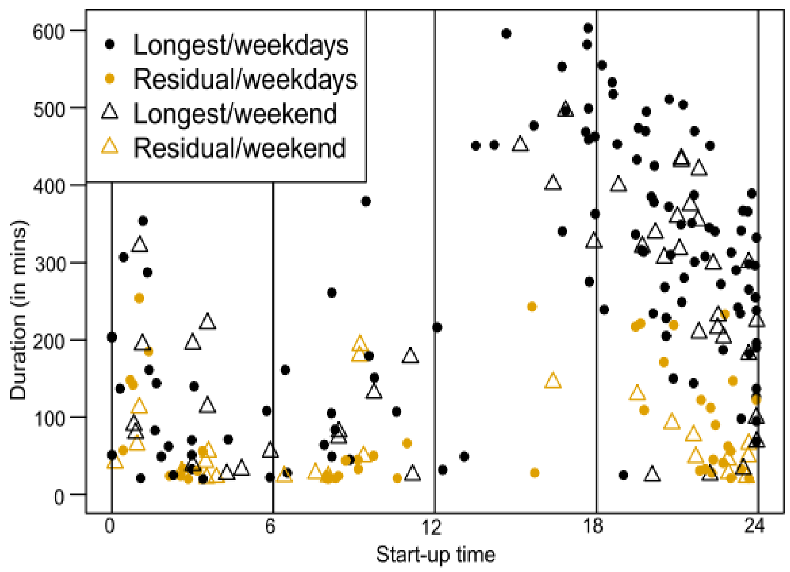

Figure 2. Charging start time and duration for EVs for one year.

Distribution System Impacts

The distribution system is the final phase of the power grid as a whole. Its purpose is to deliver electricity to residential, commercial, and smaller industrial consumers. The distribution system normally operates with a primary 13.8/34.5 kV and a secondary 380/220/127 V in most parts of Brazil.

In the eyes of the distribution system operator, EVs are new electrical loads added into the system, which can connect and disconnect from the grid at various points and moments in time. The state-of-charge of the EVs batteries will impact their behavior at the distribution grid, as well as the type of EV charger that will be chosen. When the largest amount of EVs is connected at the same time, the power system demand will increase, overlapping the previously existing demand, which could result in overloads and congestion in the power grid lines.

Usually, the peak demand time for EV charging is the same as the peak demand of the electrical grid, from 18:00 to 21:00, as previously presented in Figure 2. Adding new loads to the already stressed power system can cause issues regarded the grid's reliability.

Khalid and coauthors [17] found that for the United Kingdom power grid a 10% increase in EV load causes an 18% increase in the demand of the utility system.

According to Hartmann and Özdemir [18], the substitution of the whole German car fleet to electric vehicles (42 million vehicles) will increase the daily average fluctuation of the demand by 92%, going from 20 to 38.4 GW. Figure 3 presents the electrical demand during a week for this scenario.

Assuming the power grid can generate the amount of power demanded at a given moment, the constraints would be during transmission and distribution of energy, primarily due to transformer power limitations and conductive losses.

Khalid and coauthors [17] have shown that for EV penetration as low as 20%, the voltage deviation caused by charging is 12.7%. For high penetration levels, this deviation can reach 43.3%. In the UK, on a low voltage distribution network with 50% to 100% penetration of EV load, the voltage limits are exceeded even at slow charging.

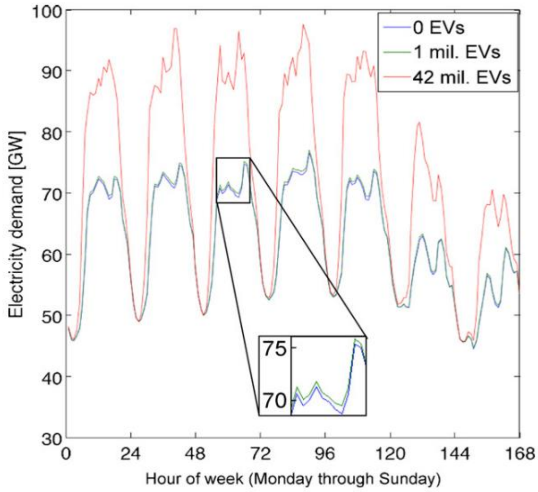

Figure 3. Energy demand for different amounts of EVs in Germany.

Case of Study

For the present work, the simulations were done using the GridLab-D software. GridLAB-D is designed as an open-source tool, developed by Pacific Northwest National Laboratory (PNNL) in collaboration with industry and academia through funding from the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability. It was designed to effectively model and evaluate smart grid technologies, such as distributed generation and demand response [19].

The island's power system consists of the main power plant, composed of five diesel generators, totalizing an installed generation capacity of 4.978 MW and a backup power of 1.12 MW. Besides the main power plant, energy to supply the island also comes from two separate solar photovoltaic plants (named FEN 1 and FEN 2), with a total installed capacity of 930 kW, capable of generating 1,400 MWh/year, according to the local system operator [20]. The output power provided by the solar plants is a function of the solar irradiance at a given time in the simulation. These values are obtained from historical meteorological data. As the focus of the present work is to evaluate the impact on the power grid, the scenario with maximum radiation (clean sky irradiance day) will be considered. An energy storage system is also present on the Fernando de Noronha power system. It is composed of 2 lithium-ion battery systems, each with a rated power of 280 kW and a nominal capacity of 510 kWh. For the simulations the negative values of power indicate that the battery is supplying energy to the grid, while positive values indicate the system is consuming energy, thus, recharging the batteries.

The island's substation presents the main transformer with a power rating of 6 MVA, a secondary transformer of 45 kVA, and a capacitor bank for power factor regulation. This circuit is composed of 407 buses. The distribution system operates at a primary voltage of 13.8 kV, and a secondary voltage of 380/220 V. There is a total of 35 distribution transformers along the grid. Some consumers are connected to the primary voltage of 13.8 kV (medium voltage consumers), but most of the loads are connected to the low voltage grid, 380/220 V. The location of these consumers is presented in Figure 4, as green dots, as well as the substation, represented by the green block.

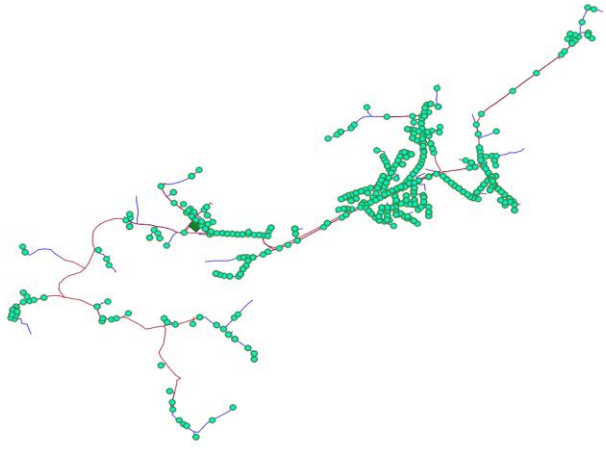

Figure 4. Location of low-voltage consumers on Fernando de Noronha distribution system.

Each load connected to the distribution grid is represented as constant power. The power consumed varies following a defined schedule, with a resolution of 10 minutes, for the entire simulation period of 24h. The load profile of the power system exhibits the typical behavior presented in Figure 5, being this profile, a result of measurements made on the island's power system.

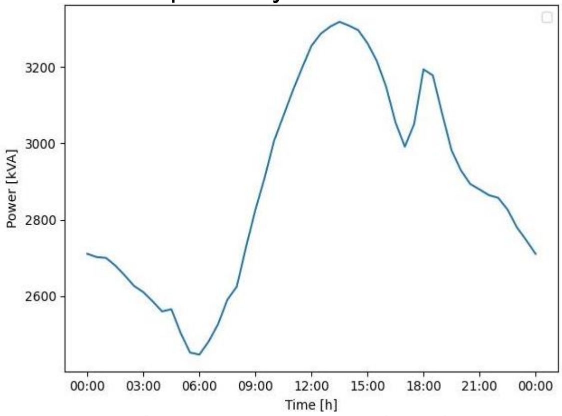

Figure 5. System load profile.

It can be noted that peak demand time is reached during the afternoon. That phenomenon is common in Brazil's power grid, mainly due to high temperatures in the afternoon, which induce a mass use of air conditioning systems.

The electrical vehicle chargers are modeled as constant power, like the rest of the loads in the power system. The characteristics of the chargers were based on generic 7.4 and 22 kW chargers available on the market. The electrical parameters of these chargers are shown in Table 1.

Table 1. Electrical Parameters for EV chargers.

Power [kW]	Voltage [V]	Current [A]	Power Factor
22	380	37.14	0.9
7.4	380	12.50	0.9

Additionally, a carport will be added to the power system, since the island presents a high potential for the placement of solar generation. A carport acts as a parking spot where vehicles can recharge, utilizing energy generated from solar panels, located at the top of the structure. The carport modeled for this study is composed of a solar panel array occupying an area of 87 m². The solar modules were defined as multi-crystal silicon, with an efficiency of 17.78% and an area of 1.97 m², resulting in a total of 44 modules and 15.47 kW of peak power. The array has a tilt angle of 5° and azimuth of 30°.

A three-phase solar inverter connects the solar array to the power grid. The inverter is rated for 12 kW of power, with a constant power factor of 1 and 98.5% efficiency. The EV charger added to the carport is the slow charger model of 7.4 kW. The parameters used to model this charger are the same as shown in Table 1.

METHODOLOGY

The methodology used to assess the impacts of the entry of electric vehicles on the island of Fernando de Noronha is illustrated in Figure 6 and will be detailed in the sequence.

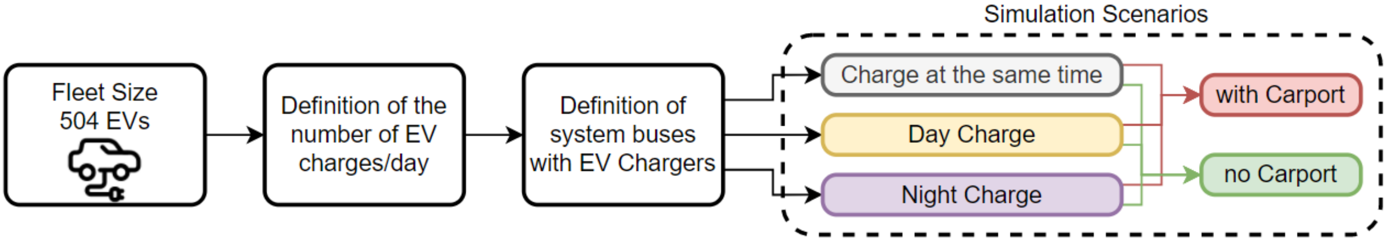

Figure 6. Methodology Flowchart.

The total amount of vehicle chargers was defined based on the mean value of distance driven per day per vehicle. This value was derived from information available in the Brazilian National Public Transports Agency (ANTP) General Report of 2018 [2]. From this report, it can be assumed that, on average, 0.40 trips per day are made using a personal vehicle, and each citizen drives 3 km per day. Therefore, each person drives 1,095 km per year, on average. According to the Brazilian Institute of Geography and Statistics (IBGE), Fernando de Noronha has an estimated population of 3,101 inhabitants [21]. In total, the distance driven per year amounts to 3,394,500 km. Also, according to the IBGE, there are a total of 1,330 vehicles on the island, out of which 504 are passenger cars. From this, it can be found that each vehicle drives about 7 km per day, on average.

For this study, only 504 cars will be taken into consideration, excluding public transport, trucks, pickups, and other motorized vehicles. Considering a consumption of 0.15 kWh/km and a battery capacity of 30 kWh for an electric vehicle and an average driving distance of 7 km per day, this vehicle would be able to drive 22 days before reaching a SOC of 20%, and therefore, recharging. For recharging all vehicles every 22 days, about 23 vehicles would need to be recharged per day. To achieve this, the charges would need to output 552 kWh per day. Considering eight 22 kW chargers, this would result in about 4 hours of charging per day. The slow charger will be limited to one, as well as the number of carports. Altogether, there will be eight 22 kW chargers and one 7.4 kW distributed along the island, totaling 183.4 kW.

These chargers will act as public charging infrastructure, therefore, need to be placed at convenient locations for the users. The criteria for deciding the charger locations were proximity to houses and/or commerce, distance to the substation, and grid parameters from the base case scenario, without EVs. As farther away from the substation, a charger is placed, the worst levels of voltage and power losses occur. However, if a charger placed far from the substation does not cause voltage limit violations or a high level of losses, it is possible to assume that, if a charger is placed near the substation, no problems will occur. The same goes for chargers placed in the already stressed busses, with high transformer loads. Based on these criteria, the location for the EV chargers, as well as the transformer power rating, is as shown in Table 2. At each bus was allocated two chargers, at least, seeing as one charger can only be connected to one vehicle at a time. The location of these buses at the Fernando de Noronha Island distribution feeder is illustrated in Figure 7.

Table 2. EV Chargers Locations.

Charger Number	Power [kW]	Bus Number	Transformer Power Rating [kVA]
22-1	22	95	75
22-2	22	95	75
22-3	22	82	112.50
22-4	22	82	112.50
22-5	22	86	225
22-6	22	86	225
22-7	22	25	45
22-8	22	25	45
7-1	7.4	95	75

Figure 7. Location of the Buses with EV Chargers, the substation (SUBS), and the solar generation power plants (FEN 1 and FEN 2).

The simulation scenarios were defined based on the period that electrical vehicles would recharge. Three main cases were created: all charges at the same time, day charging, and night charging. In the first scenario, all the nine chargers will be recharging EVs at the same time, to simulate the worst scenario for the grid. All chargers were set to be on during the period of 12:00 to 18:00, coinciding with the power system's peak demand time. Considering an average battery capacity of 30 kWh per vehicle, with a depth of discharge of 80% (initial SOC of 20% for BEVs), the total energy available during the periods that the rechargers are considered can fully recharge 38 vehicles in these 5 hours. According to the methodology for chargers' definition aforementioned, it is the desire to have the possibility to recharge at least 23 vehicles per day to supply the entire fleet of 504 vehicles.

In the second scenario, the charging is distributed along the day between the various charging stations. The schedule followed for this case is presented in Table 3**Erro! Fonte de referência não encontrada.**. Each pair of chargers located on the same bus will operate at the same defined schedule. The slow charger (7-1) will operate for the longest amount of time since it delivers the lowest amount of power. The goal in this scenario is to determine how charging EVs at the same time impacts the distribution grid.

In the third scenario, charging is done only at night, when the overall load of the system is lower, but solar generation is no longer present, with the grid relying solely on diesel generators and battery storage systems. The schedule adopted for each charger is as shown in Table 4. As in the previous case, each pair of chargers located at the same bus will operate at the same defined schedule and the slow charger (7-1) will operate for the longest amount of time.

These charging periods were defined based on the most prone hours that charges could happen. Besides, the different charging periods were designed in a given way to present different impacts on power grid operation.

Table 3. Chargers schedule for a day charging scenario.

Charger Number	Bus Number	Schedule
22-1	95	10:00 – 13:00
22-2	95	10:00 – 13:00
22-3	82	12:00 – 18:00
22-4	82	12:00 – 18:00
22-5	86	10:00 – 13:00
22-6	86	10:00 – 13:00
22-7	25	12:00 – 18:00
22-8	25	12:00 – 18:00
7-1	95	08:00 – 17:00

Table 4. Chargers schedule for a night charging scenario.

Charger Number	Bus Number	Schedule
22-1	95	00:00 – 07:00
22-2	95	00:00 – 07:00
22-3	82	20:00 – 00:00
22-4	82	20:00 – 00:00
22-5	86	00:00 – 06:00
22-6	86	00:00 – 06:00
22-7	25	20:00 – 00:00
22-8	25	20:00 – 00:00

For each of the three scenarios, a carport was added to the simulation, to inspect its effect on the distribution grid, being simulated the scenario with and without the carport placement, in a total of six scenarios. The carport was added to Bus 30, which previously had no charger connected to it. Bus 30 is connected to a transformer with a power rating of 150 kVA. The schedule for the carport charger in each of the scenarios is presented in Table 5.

Table 5. Schedule for carport charger in each scenario.

Scenario	Carport Charger Schedule
All On	12:00 – 18:00
Day Charging	08:00 – 17:00
Night Charging	20:00 – 07:00

Initially, a power flow simulation was done without the insertion of the EV chargers, aiming to define a base case scenario, that will be used as a basis for result comparison for the cases with EV penetration. 24 hours were simulated, with a resolution of 10 minutes.

The analysis for each scenario consists of identifying the impact of electric vehicle charging, in comparison with the base scenario results. As these extra loads increment the overall demand of the grid, and thus, increase voltage drops along with the system, the bus voltages are verified to check any voltage limit irregularity. For the distribution grid, voltage limits are considered adequate when between 0.93 and 1.05 p.u, according to the Brazillian Regulatory Agency (ANEEL). The voltages are then compared between the various scenarios, to establish the best and worst cases for voltage drops.

The power demand at each bus, and for the system, is also verified, in each scenario, checking if any transformers or cables are overloaded. The three scenarios are then compared to each other, to determine the best and worst cases in terms of system overloading.

At last, the overall power losses for the grid are compared. The intent is to verify which scenario results in the most and least amount of power losses in the system.

RESULTS

From the six defined scenarios detailed in the previous section, the simulations for all scenarios were made on GridLab-D. Table 6 presents an overview of all scenarios to be detailed in this chapter. Each case varies the time in which the electrical vehicles recharge, as well as the presence or not of an additional carport charger equipped with photovoltaic generation. Additionally, the base scenario will serve as a benchmark of the power system without the presence of EV chargers.

Table 6. Simulation Scenarios.

Scenario	Period of Charging	Presence of Carport
Base Scenario	No Charging	No
Scenario 1	All chargers on at the same time	No
Scenario 2	All chargers on at the same time	Yes
Scenario 3	Day charging	No
Scenario 4	Day charging	Yes
Scenario 5	Night charging	No
Scenario 6	Night charging	Yes

The following sections will detail the base scenario, as well as the scenarios that resulted in the best and worst parameters for the distribution grid.

Base Case

Based on the real data information from the distribution grid, the power flow simulation was performed.

The overall load of the system for the base scenario reaches a peak demand value of 3,318.53 kVA at 13:30 The total energy consumed during the day totalizes 69,772.99 kWh.

The demand profiles for the five buses that will receive electrical vehicle chargers are presented in Figure 8, for buses 25, 82, 86, and 95, and Figure 9 for bus 30. It is seen that buses 82, 86 and 95 have a very similar behavior, while the others present variation in load behavior, including different times for the occurrence of the peak, as is the case of bus 30. The peak demand values on the buses that will receive the chargers, as well as the hour that peak demand occurs are presented in Table .

It can be noticed that buses 25, 82, 86 and 95 have a similar profile to the grid's overall load pattern, with peak demand times occurring between 13:00 and 14:00. Bus 30, unlike the others, has peak demand happening at 18:30, due to the characteristics of the load connected to this bus. Bus 25 is the least loaded bus between the four chosen to receive EV chargers, with a peak demand of just 5.90 kVA. Bus 86 is the most loaded bus, with a peak of 236.09 kVA. About, the bus transformer power rating, bus 95 presents the worst scenario, with its peak demand reaching 152.45% of its transformer's power rating. Buses 30 and 86 also register peak demands above their transformer power rating, while buses 82 and 25 have peak values below their power rating.

The minimum voltage values and the time at which they happen, for the five buses, are presented in Table 7. Buses 25, 82, 86 and 30 do not present voltage limit violations in this scenario. At this point, it is important to highlight that, according to the ANEEL, the adequate voltage levels are between 0,93 and 1,05 p.u.. Bus 95 presents the worst voltage profile out of all five buses, with values below 0.93 p.u. occurring. The minimum voltage value for this bus happens at 16:00, with phase A reaching a voltage level of 204.45 V, which is also the minimum value on a low voltage bus considering the whole distribution grid.

Bus 35, which will not receive any EV charger, is the overall worst performing bus connected to the low voltage system, registering a minimum voltage value of 204.35 V for Phase B at 11:00, this being the only voltage limit violation that occurs in this scenario. No voltage limit violations were found on buses connected to the 13.8 kV grid.

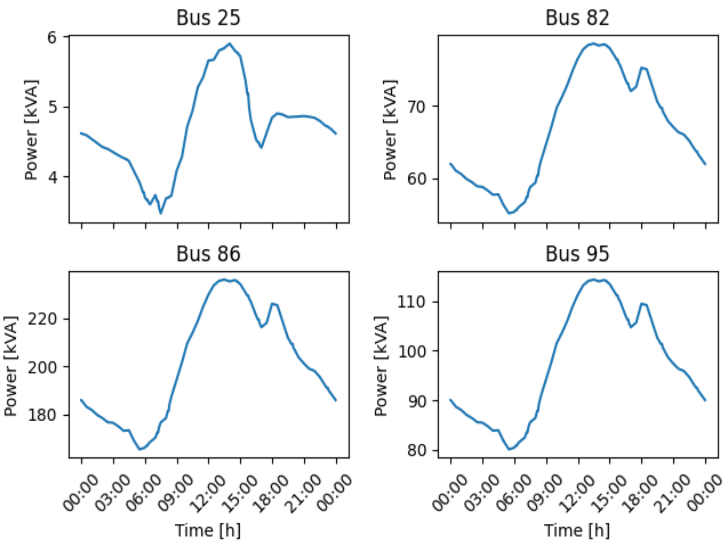

Figure 8. The power demand for buses 25, 82, 86, and 95.

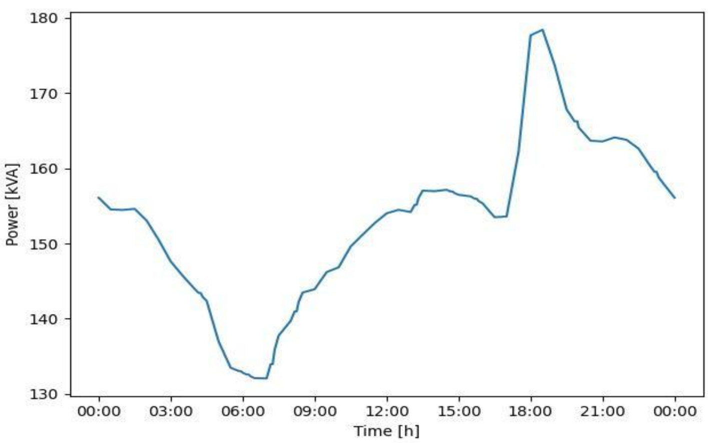

Figure 9. Power demand at bus 30.

The peak value of power losses equaled 84.12 kW happening at 13:30, since at this moment, demand is the highest and thus there is an increase in power flow. In total, the line losses during the day accumulate 799.37 kWh, and the transformer losses 864.74 kWh. The total grid losses correspond to the sum between line and transformer losses totalizing 1,664.11 kWh. This value corresponds to 2.39% of the total energy consumed.

Table 7. Peak Demand Value and Time for Base Case.

Bus	Peak Demand [kVA]	Percentage of Transformer Power Rating	Peak Demand Time [h]	Phase A Minimum Voltage [V]	Phase B Minimum Voltage [V]	Phase C Minimum Voltage [V]	Minimum Voltage Time [h]
25	5.90	13.11%	14:00	216.61	216.82	217.20	03:00
82	78.65	69.91%	13:30	210.73	210.63	212.26	15:00
86	236.09	104.93%	14:00	207.64	209.55	210.86	23:00
95	114.34	152.45%	13:30	204.45	208.43	210.46	16:00
30	178.41	118.94%	18:30	212.46	211.08	212.97	05:00

Best Scenario

Scenario 6 presented the best results. Charging solely at night resulted to be the best strategy out of the three proposed. The addition of the carport as an extra energy resource near to the loads also improved the overall grid parameters.

The peak demand reached 3,318.53 kVA at 13:30. This value is the same as the one found for the base case. This is to be expected, as no new loads were added to the system during the peak demand time. The total energy consumed totalizes 70,861.64 kWh, presenting a 1.56% increase compared to the base case.

Peak demand values for the five buses with EV chargers are shown in Table 8. Buses 25, 82, and 95 present an increase in peak demand value. For those three buses, the peak demand time is shifted from the afternoon to the night. This coincides with the EV charging schedule for each bus, indicating that the main contributor to this event is vehicle charging. Bus 86, on the other hand, maintains its peak demand during the afternoon, seeing no increase or decrease to its value. As this bus is the most loaded bus out of all four, the two chargers installed do not have that same impact as in the other locations. Bus 30 does not see an increase in peak demand, maintaining its peak time at 18:30. As the charging starts at 20:00 for that particular bus, the 7.4 kW charger placed was not enough to shift the peak demand to a later hour. The demand at bus 30 during the afternoon was found to be lower when compared to the base scenario. This indicates the carport is exporting energy from solar generation to the power grid, as expected.

Transformer overloading occurs at buses 30, 86, and 95, with peak values reaching 118.92%, 104.93%, and 181.81% respectively. Buses 25 and 82 do not register any values above 100%, but get close, reaching 98.87% and 96.83%, respectively.

Buses 25, 82, 86 and 30 do not register any voltage limit violations. For buses 25, 82, and 30, the minimum voltage value was registered during the EV charging period. Bus 25 has its minimum value coinciding with the peak demand time as well. For bus 86, the minimum value occurs during the afternoon, close to the peak demand time.

The minimum voltage value for the five buses is presented in Table 8. Bus 95 presents the worst performance out of all five buses. The minimum values are reached during the vehicle charging period, as seen with the other buses, but only for this location, the voltage limits are violated. Apart from the minimum value registered at 06:00, violations also occur at 23:00. When compared to the base case, no voltage drops under 0.93 p.u. occur during the afternoon, which could indicate that the additional solar generation outputted from the carport is improving the voltage values for this bus. For the buses without any vehicle chargers, bus 35 registers voltage limit violations occurring at 02:00, 08:00, 09:00, 10:00, and 15:00, with a minimum value of 204.35 V (in low voltage) occurring at 02:00. No voltage limit violations were registered on buses connected to the medium voltage grid.

Table 8. Peak Demand Values and Times for Scenario 6.

Bus	Peak Demand [kVA]	Percentage of Transformer Power Rating	Peak Demand Time [h]	Peak Demand Increase %	Phase A Minimum Voltage [V]	Phase B Minimum Voltage [V]	Phase C Minimum Voltage [V]	Minimum Voltage Time [h]
25	44.49	98.87%	21:00	654.07%	213.82	214.04	214.39	21:00
82	108.93	96.83%	20:00	38.50%	210.66	210.51	211.92	04:00
86	236.09	104.93%	13:30	0.00%	207.65	209.55	210.86	14:00
95	136.36	181.81%	00:00	19.26%	204.45	208.43	210.06	06:00
30	178.38	118.92%	18:30	-0.02%	212.46	211.08	212.98	06:00

The peak loss has a value of 83.72 kW and happens at 13:30. In total, the line losses during the day accumulated 846.92 kWh, and the transformer losses 903.15 kWh. The total grid losses, the sum between line and transformer losses equal 1,750.07 kWh. The peak loss is 0.48 % lower in comparison to the base case, while the total losses are 5.17% higher and amount to 2.47% of the total energy consumed.

Worst Scenario

Scenario 4 presented the worst overall results. It had the highest total grid losses, as well as the highest number of voltage limit violations out of all six scenarios.

The peak demand has a value of 3,483.13 kVA and happens at 12:50. In comparison to the base case, this value is 4.96% higher. The total energy consumed equals 70,631.49 kWh, an increase of 1.23% compared to the base case.

The four buses without the carport present peak demand increase, when compared to the base case. Bus 30, on the other hand, presents a minor reduction in its peak demand, varying -0.02%. As this bus has its peak later during the evening, it is not affected by the vehicle charging.

Overall, transformer overloading is a problem. All buses register peak demand values higher than their transformer's nominal power rating. The worst bus in this criterion continues to be bus 95. The peak demand value and time for all five buses are presented in Table 9.

The minimum voltage value for the five buses with EV chargers is also presented in Table 9. Buses 25, 82, 86 and 30 do not register any voltage limit violations, however, they are constantly under the nominal value of 220 V (low voltage). Bus 95 registers the overall minimum voltage value for the whole of the low voltage grid, reaching 201.92 V on phase A at 20:00. Besides, voltage drops also occur at 00:00, 01:00, 03:00, 06:00, 22:00 and 23:00. Resulting in seven voltage limit violations for this single bus.

Table 9. Peak Demand Values and Times for Scenario 4.

Bus	Peak Demand [kVA]	Percentage of Transformer Power Rating	Peak Demand Time [h]	Peak Demand Increase %	Phase A Minimum Voltage [V]	Phase B Minimum Voltage [V]	Phase C Minimum Voltage [V]	Minimum Voltage Time [h]
25	45.52	101.16%	14:00	671.53%	213.87	214.16	214.51	08:00
82	118.27	105.13%	13:30	50.38%	209.17	209.06	210.68	03:00
86	274.54	122.02%	12:50	16.29%	206.60	208.49	209.78	22:00
95	160.07	213.43%	12:50	39.99%	201.92	205.93	207.95	20:00
30	178.38	118.92%	18:30	-0.02%	212.46	211.08	212.96	06:00

For this scenario, bus 35, which did not receive any EV charger, registers a voltage limit violation at 09:00, reaching 204.12 V on phase B. No buses register minimum voltage values during the period that EV charging is present. Although bus 25 registers its minimum value at 08:00, being the EV charging at that bus scheduled from 12:00 through 17:00. No voltage limit violations were registered on buses connected to the medium voltage grid.

The peak loss has a value of 96.92 kW and happens at 12:50. In total, the line losses during the day accumulate 855.93 kWh, and the transformer losses 918.09 kWh. The total grid losses correspond to 1,774.02 kWh. The peak loss is 15.21% higher compared to the base case, and the total losses are 6.60% higher and amount to 2.51% of the total energy consumed.

Scenario Comparison

As seen from the previous sections, varying the time at which the recharging of the electrical vehicle occurs can cause different levels of impact on the distribution grid. Charging at peak demand time or during low demand periods has a different impact on the system.

Table 10 presents the peak demand value reached on all 6 scenarios, as well as the results from the base scenario.

Table 10. Peak Demand Comparison.

Scenario	Peak Demand [kVA]	Peak Demand Increase %	Energy Consumed [kWh]	Energy Consumption Increase %	Total Losses [kWh]	Total Losses Increase %
Base Case	3,318.53	-	69,772.99	-	1,664.11	-
Scenario 1	3,501.85	5.52%	70,873.19	1.58%	1,764.46	6.03%
Scenario 2	3,509.26	5.75%	70,917.66	1.64%	1,762.82	5.93%
Scenario 3	3,483.13	4.96%	70,631.50	1.23%	1,767.33	6.20%
Scenario 4	3,483.13	4.96%	70,631.49	1.23%	1,774.02	6.60%
Scenario 5	3,318.56	0.00%	70,808.52	1.48%	1,759.42	5.73%
Scenario 6	3,318.56	0.00%	70,861.64	1.56%	1,750.07	5.17%

Scenario 2 presents the overall highest peak demand increase, reaching 3,509.26 kVA. Scenario 1 comes closely behind, registering a peak of 3,501.85 kVA. Not coincidently, both scenarios coincide the charging period with the grid's peak demand. Scenarios 5 and 6 have peak demand values equal to the base case. As charging occurs only at night for both cases, no impact on peak demand is caused by this strategy. Scenarios 3 and 4 present peak demand increases, but not as high as in scenarios 1 and 2, mainly because a part of the charging occurs during the morning when the overall grid demand is not as high as during the afternoon.

The impact of charging can also be realized when the buses which received the chargers are analyzed. For the base scenario, buses 86, 95, and 30 already register transformer overloading, reaching power demands over 100% of their respective transformer's power rating. With the placement of the EV chargers the problem is aggravated. In all scenarios, all buses registered a peak demand value of at least 90% of their respective transformer's nominal power rating. Bus 95 is the overall worst performing bus in all scenarios. For the base case, it already reaches 152.45% of its power rating. For day charging, scenarios 1 through 4, bus 95 registers peak demand of above 200% of its power rating. When night charging is applied, this can be reduced to 181.81% but remains as the most overloaded bus. Probably, if a charger for EVs is to be installed in this bus, the transformer will need to be replaced to avoid overloading the current equipment.

With the demand increases, the system losses also registered an increase. Table 10 also shows a comparison between the system losses for each scenario.

As stated in the sections above, the night charging strategy presents the best results in terms of system losses, with scenario 6 presenting the lowest increase in losses out of all cases simulated. For the scenarios in which day charging was applied, the total losses increase was found higher when compared to the night charging cases. Even the additional carport added to the system did not help reduce losses, with scenario 4 resulting in the highest overall loss increase out of all cases.

For all scenarios, only two buses registered voltage values below the 0.93 p.u. limit, those being 95 and 35. Bus 95 was already fairly overloaded before the addition of the chargers and registered voltage limit violations during the base case. Bus 35 also registered violations during the base scenario but did not receive any vehicle charger. Overall, the lowest minimum values for bus 95 were registered for scenario 1, with phase A reaching 201.61 V (at low voltage). This scenario is also when bus 95 is most overloaded.

When considering the total number of voltage limit violations on bus 95, scenario 4 presents the most, with seven total violations. Scenarios 1, 2, and 3 all register six limit violations, while scenarios 5 and 6 present the best-case, with only two violations occurring. For the medium voltage buses, all values remain above 0.98 p.u. for all scenarios.

As it can be seen, scenarios 5 and 6 present no peak demand increase, the lowest transformer overloading for buses with EV chargers, and the lowest increase in overall total system losses.

This would be expected, as charging away from peak hours reduces the stress on the distribution system. This impact is similar to the results found by Dogan and coauthors [7] and Marmaras, Xydas, and Cipcigan [8]. Charging at off-peak hours has a valley-fill effect and allows for a greater insertion of electric vehicles without compromising the power grid.

CONCLUSION

This study intended to determine the impact caused on the distribution grid by adding electric vehicles to Fernando de Noronha Island. To achieve this, the current grid infrastructure was analyzed, being modeled at GridLab-D software. Through this model, it was possible to add electrical vehicle chargers to various points along the island's distribution grid. The locations of these chargers were made to reflect real-world use, placing them at points where demand for vehicle recharging would be high, mainly near commercial and residential areas. Different charging scenarios were also specified, to determine the worst and the best period for charging, considering the impact that they can cause on the power grid.

The impacts to the grid vary along with the charging strategy adopted. Charging during the day and afternoon was shown to be the worst possible case, presenting the highest increase in peak demand and total system losses, while also causing buses with chargers to become overloaded and present voltage drops beyond acceptable limits. Overall, the usage of the carport charger during the day did not improve the grid parameters, with peak demand levels, total system losses, and voltage profiles remaining similar to the scenarios without the carport. When charging at the carport is only done at night, the peak demand does not increase, and the total system losses have the lowest increase of all six scenarios. For this case, the carport acts solely as a distributed generation resource, providing power to the rest of the grid. As peak demand occurs during the afternoon, adding a solar power source close to the system loads, decreases the losses suffered by the grid. Adding extra solar generation plants near the vehicle chargers and other loads could help further mitigate the total system losses throughout the day.

It should be noted that a worst-case scenario is simulated in this study, with all chargers operating at the same time, for a continuous period. Depending on the size of the fleet and their mobility characteristics, the use of all nine chargers at the same time might not be necessary, thus decreasing the overall impact on the power system and distribution grid. The buses chosen to add the chargers were also not chosen to optimize the grid's performance, but instead solely with user demand in mind. Based on the worst-case results, with the EVs recharging simultaneously during the day, it should be necessary to improve grid operation by the replacement of some overloaded transformers and the installation of voltage regulators to avoid voltage violations.

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