Analysis of the Integration of an Electric Bus and an Electric Vehicle with Grid-Connected PV Systems and a Storage System

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Abstract

This paper aims to analyze the electricity consumption of an electric bus (eBus) and a passenger electrical vehicle (EV) in order to investigate the viability of powering such vehicles with grid-connected solar photovoltaic (PV) systems. The integration of a battery to the system is also explored, with the analysis of two different energy management strategies. The analysis is based on energy production data of building-integrated PV systems in the Fotovoltaica/UFSC laboratory (www.fotovoltaica.ufsc.br), and consumption measurements of the laboratory's eBus, which makes 5-daily-round trips of 52 km each, and a Renault Twizy electric vehicle. The results showed that the PV systems can play an important role in reducing the high-load demand generated by electromobility. However, the addition of a battery for storing the surplus of PV energy would be advantageous to decrease the grid consumption and reduce the dependence of the public grid, demonstrating both technical and economic benefits.

Keywords: Electromobility, PV systems, Storage Systems.

1. Introduction

Concerns regarding the emission of greenhouse gases, such as CO_2, and the diversification of the world's energy mix have made public and industrial sectors view electric vehicles (EVs) as an attractive solution. EVs can reduce the total CO_2 emissions even in electricity systems supplied mainly by fossil fuels, due to the high efficiency of electric motors (Richardson, 2013). In 2018, the Brazilian Federal Government proposed an initiative for the automotive industry: Rota 2030 (Ministério da Economia, Indústria, Comércio Exterior e Serviços, 2018), that will provide some favorable conditions to the growth of this market. The IPI (Tax on Industrialized Products) of EVs will be reduced, there will be a quality labeling system and EVs will have standard security items (Machado et al., 2018). With the worldwide incentive, by 2040 at least 57% of all new vehicles sales and 30% of the global fleet of passenger vehicles are expected to be electric (McKerracher, 2019).

However, the most positive impact of EVs is the potential to assist in the expansion of renewable energy sources (Richardson, 2013). Since 2015, decentralized power generation installations have been expanding in Brazil, mainly with photovoltaic (PV) systems, recently surpassing 1 GWp of installed power capacity (ANEEL, 2019). This growth derives from the increase in energy tariffs, cost reduction of PV systems, the low-environmental impact of PV and the increase of efficiency that PV systems provide to the grid. Distributed PV generation emerge as a more efficient and more reliable alternative to the traditional energy electrical systems (Mitscher and Rüther, 2012). Thus, PV systems can be installed anywhere, and because both the solar energy resource and the energy demand in urban buildings have a distributed character, their integration to urban buildings and interconnection to the public electricity grid are the latest trend in this area. They are even more advantageous when combined with EVs, due to the possibility of using building roofs as a source of energy for local charging, besides being easily implemented and interconnected to the distribution network (Rüther, 2004).

As a barrier regarding renewable energy is its unpredictability, the integration of Energy Storage Systems (ESS) and PV systems is seen as a solution, besides the electromobility, to provide the level of power quality and reliability that the grid demands (Zahedi, 2011). The batteries are, therefore, essential for the penetration of both electromobility and renewable energies. For this reason, the aim of this study is to analyze the electricity consumption of an electric bus (eBus) and a passenger EV in order to investigate the viability of powering such vehicles exclusively with grid-connected PV systems and also analyzes the addition of an ESS into the

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system and the effects of its integration.

2. Methods

This study was based on the Fotovoltaica/UFSC solar energy laboratory at Universidade Federal de Santa Catarina in Florianópolis-Brazil (www.fotovoltaica.ufsc.br), which integrate 110 kWp of PV on buildings and ground, as shown in Fig. 1. The image also shows the eBus and the EV used for the analysis, that is also presented in Fig. 2.

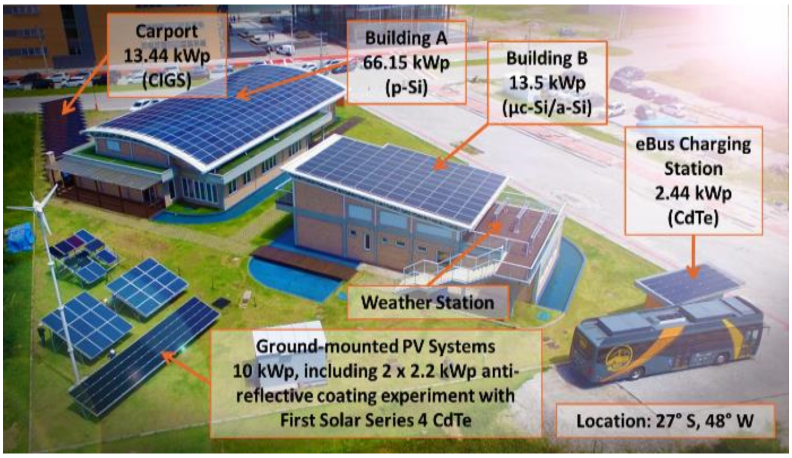

Fig. 1: The Fotovoltaica/UFSC solar lab, and the 110 kWp PV systems.

Fig. 2: The eBus and the EV used in this analysis.

2.1. Electric Bus (eBus)

The use of electric buses is a worldwide trend and the automotive industry has been investing in the development of battery and powertrain technology. The UFSC eBus started the regular transportation service between the university's main campus and the Fotovoltaica/UFSC Laboratory in March 2017, and, since then, the 26-km route has been monitored under real traffic conditions. The eBus performs five 52-km trips (2 x 26 km each trip) per day and ran over 100,000 km throughout the first two years of regular service. It is totally powered by the PV systems installed in the Lab. Fotovoltaica/UFSC, at Sapiens Parque, Florianópolis-SC, as shown in Mattes et al. (2018).

The eBus has 38 passenger seats and two meeting tables, wireless network, outlet plugs (220V and USB) and air conditioning, in order to provide a working environment during the journeys. After each round trip, the e-

Bus is recharged at Sapiens Parque in a 75 kW charger. The transportation service is free of charge for the UFSC community and the project was funded by the Ministry of Science, Technology and Innovation (MCTI, currently MCTIC) together with the partnership of the companies WEG, Eletra, Marcopolo and Mercedes-Benz.

2.2. Electric Vehicle (EV)

The EV applied in this analysis is a Twizy, shown in Fig. 2. It is an electric car for use in urban perimeters developed by Renault, with space for two people, maximum speed of 80 km/h and autonomy of approximately 100km. In December 2016, it arrived in Brazil in a joint project between Renault and the binational hydropower plant Itaipu, which was used in the context of the Mobi-I project. As part of this project, several Twizys were assembled in the Itaipu plant, and they are used to assist in the logistics of mobility within the complex, such as internal transportation of people, etc.

As UFSC, Itaipu and PTI (Itaipu Technological Park) maintain a partnership agreement for the research of innovative technologies in favor of the environment focused on the area of electromobility and solar energy, Itaipu made a Twizy available to Fotovoltaica/UFSC, with the purpose of research development and even transportation within the Sapiens Park, bringing this technology closer to the Brazilian academic community.

2.3. Energy Consumption Analysis

The evaluation of the eBus consumption of the eBus was based on measurements carried out at the 75 kW charger, on the monitoring worksheet completed by the drivers in their daily routine, and on the data provided by the vehicle's Battery Management System (BMS). For EV consumption analysis, measurements of the grid consumption during the charging in a typical electrical outlet socket have been performed. For the two vehicles evaluation, their normal daily routine was assumed, that consists of five trips of the eBus to the main campus of the university and one trip per day of the Twizy, with charging after each trip. For PV production evaluation, real data of the laboratory grid-connected systems were used. In the months that the information about PV energy production was not available, some filling data techniques were applied. The study analyzed the system since the beginning of the eBus regular operation.

2.4. Energy storage

To analyze the technical viability of the addition of a storage system to the laboratory building, several simulations were performed, in order to test different storage capacities and two different dispatch approaches to achieve an optimum alternative:

- Case 1: The battery is used to store excess PV energy, in order to use it at any time when PV production is not enough to supply energy to all the loads;
- Case 2: The battery stores the excess PV energy during the day (low-rate energy tariff) and is used to supply loads during peak hours (high-rate energy tariff).

The simulation was performed using real data of PV energy production and EVs consumption of 2017 and 2018.

3. Results

3.1. Energy Impact of Electric Bus (eBus) Charging

The impact of the eBus on the grid is quite substantial. It surpasses 70 kW of power during the five times it is charged daily. For this reason, the PV systems installed have an important role in the reduction of the power demand from the grid during the day. Fig. 3(a) shows an example of data obtained on a clear-sky day in December 2017, while Fig. 3(b) is an example of a rainy day in the same month. It is visible that, for the first case, a large part of the eBus instantaneous consumption is covered by the PV generation. It is interesting to notice, that in the second charging period of the day, the charger needs are fully fulfilled by PV energy. This is an important result because in the last years, in Brazil, the midday hours are intensive in energy consumption in the summer, because of air conditioning loads (Empresa de Pesquisa Energética, 2015). It thus shows that the eBus is not adding to the problem, due to the PV generation. In the second case (Fig. 3(b)), the PV generation is not as significant as before but still reduces the power load generated by the eBus.

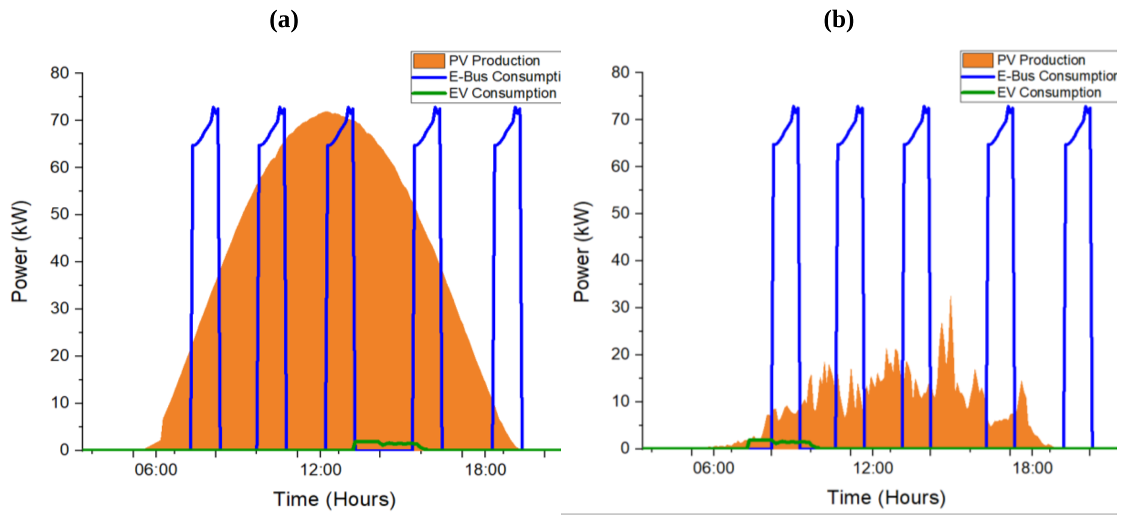

Fig. 3: Examples of PV production compared to the eBus Consumption and the EV Consumption on different meteorological conditions days: (a) clear-sky (b) rainy day.

Tab. 1 presents the PV energy production and consumption values of the eBus monthly, since the beginning of its operation. In most part of the year, the PV energy production will cover a large part of the eBus consumption. When comparing the whole energy production and consumption of an entire year, in 2018, the total annual PV production on the laboratory was more than the double of the total eBus consumption. Some months analyzed, as of September 2018 for example, presented a low energy consumption of the eBus, caused by reduced journeys due to periodical maintenance. For better visualization of the monthly variation of consumption, Fig. 4 presents the annual variation of eBus consumption versus PV energy production in the Fotovoltaica/UFSC lab, using the mean month values of 2017 and 2018.

Tab. 1: Comparison between photovoltaic generation and consumption of eBus, EV, and buildings

Month	PV energy production [kWh/month]	eBus energy consumption [kWh/month]	Percentage of the PV production used for charging the eBus
Mar/17	7,577.8	2,514.6	34%
Apr/17	7,972.5	4,930.9	63%
May/17	4,858.6	5,990.6	125%
Jun/17	5,448.8	5,517.2	103%
Jul/17	8,196.1	5,247.7	65%
Aug/17	7,943.3	5,310.9	68%
Sep/17	8,476.5	5,690.3	68%
Oct/17	10,055.9	5,690.3	57%
Nov/17	10,542.4	6,069.6	58%
Dec/17	12,212.5	3,477.4	29%
Jan/18	10,751.1	2,676.2	26%
Feb/18	9,707.3	2,224.7	24%
Mar/18	10,855.5	6,472.1	60%
Apr/18	9,498.6	6,242.1	67%
May/18	9,185.4	5,420.3	60%
Jun/18	8,350.4	3,461.5	43%
Jul/18	8,246	5,959.0	73%
Aug/18	8,141.6	6,112.2	76%
Sep/18	10,438.0	1,596.0	16%
Oct/18	7,306.6	5,316.2	74%
Nov/18	10,542.4	4,236.4	41%
Dec/18	12,212.5	2,034.8	17%
Total	218,111.2	10,2190.8	58%
Monthly Average	9,088.0	4,645.0	52%

During the summer (December to February in Brazil), the eBus consumes less than 30% of the PV generation of the laboratory. The remaining energy is used for the building consumption and the surplus is compensated in the subsequent months, as established in the net-metering system. The mean ratio between the eBus consumption and PV production is 50%, meaning that only half of the laboratory energy generation is used for charging the EV. Therefore, it can be said that the eBus is fully powered by photovoltaic solar energy.

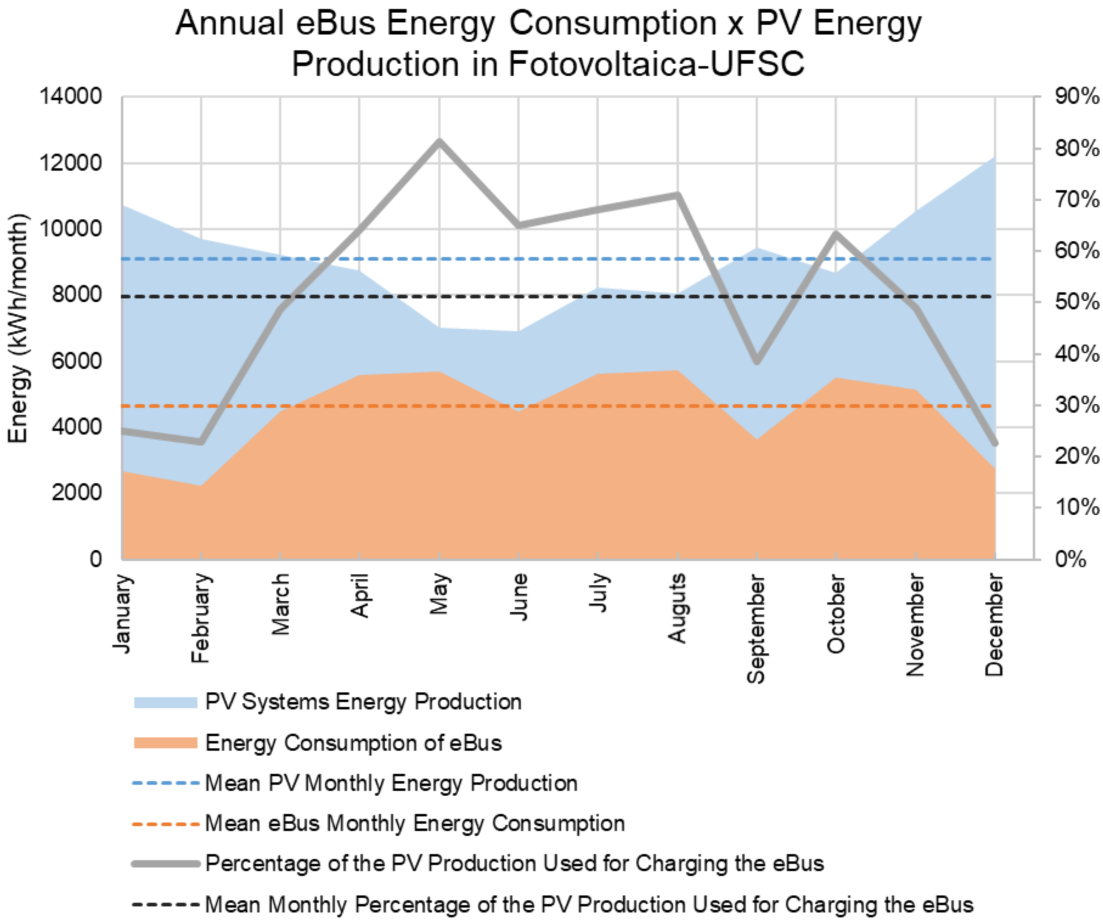

Fig. 4: Anual eBus energy consumption and PV energy production in the Fotovoltaica/UFSC laboratory.

Another energy impact of the eBus is its effect on the grid quality. The start-up of the fast-charger and its operation can interfere on the voltage level grid and inject harmonics and reactive energy to the grid. Therefore, continuous monitoring of the grid quality and correction techniques have to be implemented.

3.2. Energy Impact of Electric Vehicle (EV) Charging

The measurements showed that the impact of the charging of the EV is not significant compared to eBus consumption. The EV only consumes circa 4 kWh per day of electric energy, while the eBus consumes around 65 kWh for each of its five-daily trips. Fig. 5 presents an example of a measurement of the energy consumption for charging the EV. The charging process takes less than three hours and demands less power than an electric shower load, typically used in over 90% of Brazilian households. The data showed that based on the performance of the PV systems analyzed, the installation of a PV system of only 1,2 kWp could provide enough electricity to supply the EV daily. That means that building a small carport for this EV, covered with 4 commercial PV modules connected to the grid, would make it energy self-sufficient, equivalent to the EV footprint.

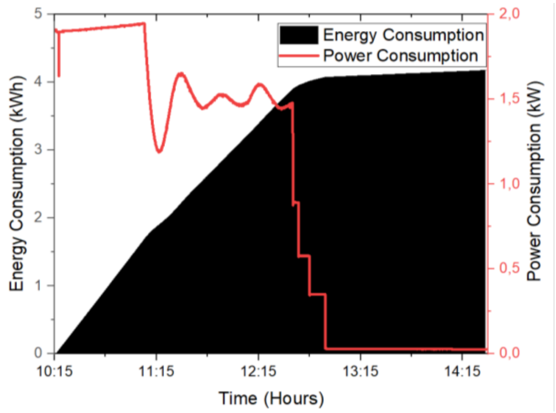

Fig. 5: Electric charging profile of the EV.

3.3. Impact analysis of implementing an energy storage system

Although the PV systems cover a great part of the EV and eBus demand during the day, the last eBus charging period occurs in the evening, when the energy tariff is more expensive than during the day. To avoid such situations, and to take the maximum advantage from the energy supplied by the sun, an alternative would be the addition of a storage system to the laboratory.

An example of a result of the simulation for the evaluation of the use of a storage system is presented in Fig.6. In the graphs, the red peaks represent high consumption of power from the grid, and the purple valleys mean injection to the grid. Fig. 6(a) shows the resulting grid profile for one week in September 2017, when the only source of energy besides the grid is PV without ESS addition. In this case, the grid is used constantly and intensively, for consumption or injection to the grid.

Fig. 6(b) presents the grid balance, in the same week, but using the battery as case 1, which stores energy whenever there is a surplus of PV and uses the power of the battery whenever there is not enough PV production. It is also charged during late-night hours when the tariff is also lower. This case mitigates the use of the grid during the day and increases the self-consumption of the building, having as little as possible energy exchanges with the grid. This is an interesting result for the case that the injection of PV energy to the grid generates extra fees. However, the consumption of power during the night period is significant and depending on the price of energy during this time, may not be advantageous.

On the other hand, in case 2, presented in Fig. 6(c), the battery stores surplus PV energy during the day as its maximum capacity, in order to save it to use it in the high-rate tariff period. It is visible that although the night peak is avoided, the energy consumption from the grid during day time is intensive. However, this case has also the advantage of storing energy in the case of a fault from the public grid.

It is assumed that the public grid is an infinite battery, which stores the excess energy and provides it back when necessary. According to Brazilian's legislation, the injected energy to the grid returns in the form of an energy credit (kWh), which is compensated at the end of each month.

For the simulations using batteries with higher storage capacities, case 2 becomes the most profitable from a technical point of view, since the battery is capable of providing energy for the evening recharge of the eBus batteries, as well as increasing the self-consumption. However, with the still high prices of storage systems, it is not economically viable yet. This situation, however, is expected to change fast with the upscaling of battery manufacturing resulting from the growing uptake of electric mobility all over the planet.

But cases present challenges for their implementation, since they require continuous monitoring of the loads and generation units of the laboratory, besides the need for environmental forecast algorithms, in order to anticipate the PV production for managing the battery charging. However, other management algorithms could be implemented, focusing on maintaining the grid quality that can be disturbed by both the eBus charger and the PV inverters.

Another possible application of the eBus is the possibility of its for injection of energy to the grid, the so-called Vehicle-to-Grid (V2G). When the EV arrives at the laboratory, after its last journey at the day, its state of charge is 40%, meaning that its battery still has around 25 kWh available to be used causing no harm to the battery. This amount of energy could be used for providing energy for the building, or even being injected to the grid, since the tariff of this time of the day is high. Such use of the eBus would require changes in the charging station power electronics but could be a less expensive alternative to buying an ESS.

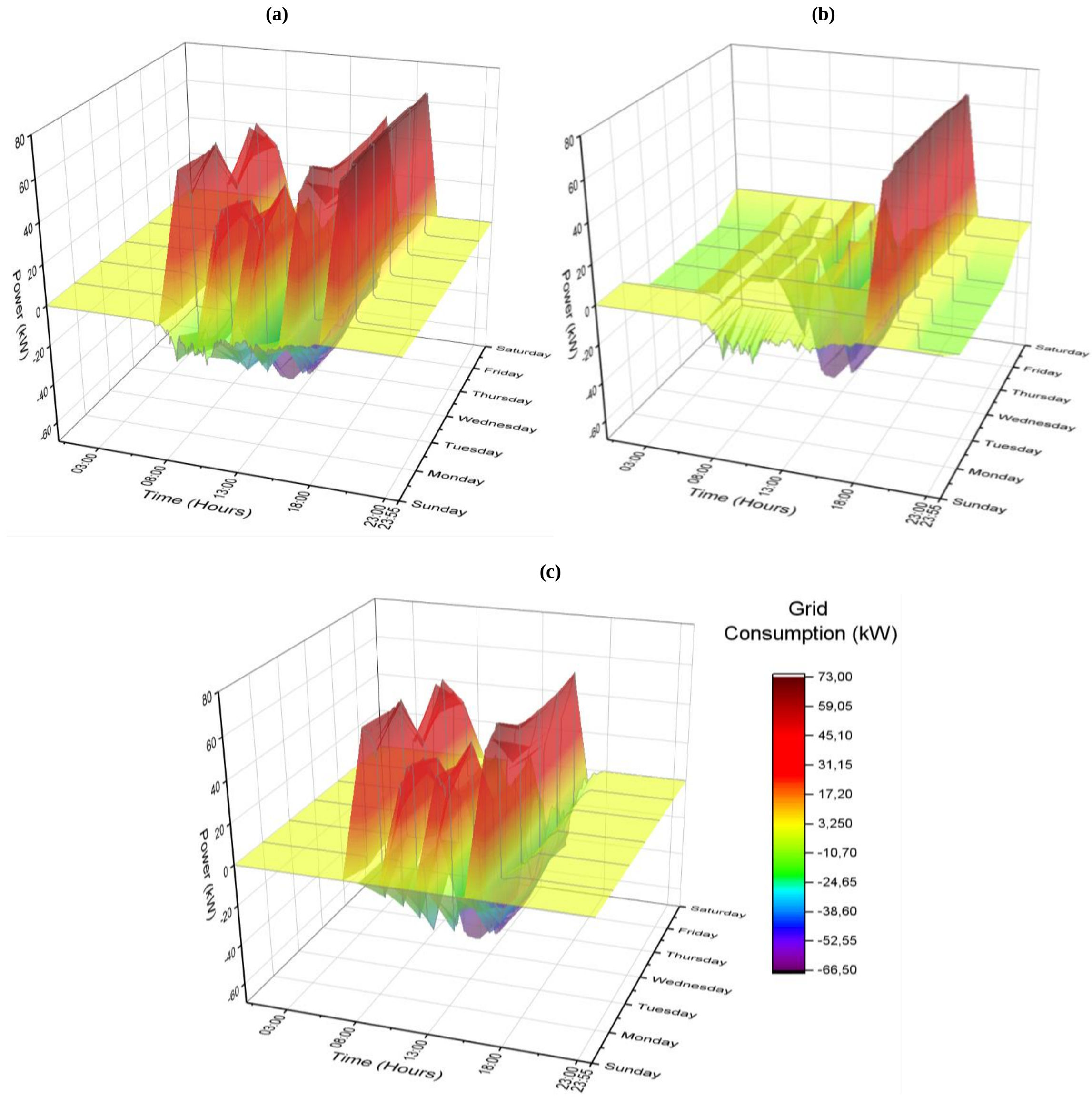

Fig.6: Example of resulting grid profile in a week in September of 2017 for three different scenarios: (a) PV production combined with EV and eBus consumption, (b) PV production combined with EV and eBus consumption and an additional storage system of 100 kWh dispatched as case 1 and (c) PV production combined with EV and eBus consumption and an additional storage system of 100 kWh dispatched as case 2.

4. Conclusions

This paper evaluated the integration of grid-connected PV systems with electromobility, as well as with a storage system (ESS). The integration of PV in buildings is already a reality in Brazil and in the world and has great potential to expand further. The measurements showed that the impact of the charging of the EV is not significant compared to the eBus consumption and that a small PV system could provide all the energy needed for powering the car. PV generation also attenuates the high-power demand of the eBus, but the addition of a battery for storing the surplus PV energy for using it to reduce the grid consumption may provide economic and technical advantages.

5. Acknowledgments

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