PERFORMANCE OF AN ELECTRIC BUS, POWERED BY SOLAR ENERGY

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4.3 – Installed Photovoltaic Systems Technical Aspects
4.4 – Photovoltaic Systems Monitoring and Control

Abstract. *This article makes an energy analysis of the Solar Energy Research and Training Center of the Federal University of Santa Catarina (Lab. Fotovoltaica-UFSC), at Sapiens Parque, Florianópolis-SC. The analysis takes into account the recharges of a full electric bus (e-Bus) used to transport researchers between the UFSC main campus and Sapiens Parque. In this study, the energy consumption of the electric bus and the generation of grid-connected photovoltaic systems in the research center were analyzed and evaluated. A data logger is connected to the inverter of the engine to monitor different parameters during the vehicle trips. The e-Bus carries out five trips a day and gets recharged during the 1.5 h break at Sapiens Parque. The monitoring of the e-Bus includes battery state of charge, regenerative braking energy production, consumption of the engine, GPS data and velocity. The evaluation of the data showed that the avg. traveling speed was an influencing factor on the consumption of the e-Bus, while the number of passengers wasn't. The analysis also showed, that the installed PV systems in the Lab. Fotovoltaica-UFSC generated more than 100 MWh in a period of one year (Nov./2016 to Oct./2017), which corresponds to a yield of 1,098 kWh/kWp per year. Since the begging of its operation, in March of 2017, the e-Bus consumption represented 75% of the PV production of the Lab. Fotovoltaica-UFSC.*

Keywords: *Electric bus, Photovoltaic, Distributed generation*

1. INTRODUCTION

Due to the current global concerns about CO_2 emissions and dependency on fossil fuels, electric vehicles are seen as an alternative to traditional vehicles. However, they increase the load on the power grid, creating a need for changes in the power system, which is a major source of greenhouse gas. Thus, the benefits of the electro mobility to the environment are strictly dependent on the use of renewable sources of energy (Saber & Venayagamoorthy, 2011).

At the same time, since 2015, decentralized power generation has been gaining ground in Brazil, mainly with photovoltaic (PV) systems (ANEEL, 2017), due to: increase in energy tariffs, cost reduction of PV systems, low environmental impact of PV electrical power generation and increase of efficiency that PV systems provide to the grid (Mitscher & Rüther, 2012). Distributed generation emerges as an option for the electric sector, being more efficient and more reliable. In this way, PV systems integrated to urban buildings and interconnected to the public electricity grid are the latest trend in this area and are justified because both the solar energy resource and the energy demand in urban buildings have a distributed character (Rüther, 2004).

Combining both critical topics, the Solar Energy Research and Training Center of the Federal University of Santa Catarina (Lab. Fotovoltaica-UFSC), at Sapiens Parque, Florianópolis, developed an electric bus (e-Bus) powered by the PV systems installed on its roofs.

The aim of this article is to analyze the electricity consumption of the e-Bus and compare it to the power generation of the grid-connected PV systems, installed in the Lab. Fotovoltaica-UFSC. The consumption of the e-Bus was monitored during operation and analyzed against load of passenger, average travelling speed and weather conditions (air conditioner).

The next subsections present the technical characteristics of the Lab. Fotovoltaica-UFSC buildings (and of its PV systems) and of the e-Bus.

1.1 Lab. Fotovoltaica-UFSC buildings and its PV Systems

The Lab. Fotovoltaica-UFSC consists of two buildings: A and B, with 450.57 m² and 174.84 m² respectively. The covers of both buildings have integration of PV modules, being 66.15 kWp on building A and 13.50 kWp on building B. In addition to the PV integration on the buildings, there is a PV system on the parking lot with 13.44 kWp, a set of 10 kWp ground structures and a PV system of 2.44 kWp on the roof of the e-Bus recharge station.

Fig. 1 presents a photo of the laboratory with all its PV systems described. As seen in the picture, the system integrated with building A has modules tilted in different angles, in order to follow the curvature of the existing cover, with slope of modules varying from row to row. Two thirds of the systems are oriented north and one third is horizontal or slightly sloping to the south. The system on building B is oriented to the north, with slope of 6° (inclined cover) and the system on the e-Bus recharge station is oriented to 36° east with slope of 3°. The parking lot is oriented to the west with slope of 5° and is shadowed by building A. Evidently most of the PV systems are not in the position to maximize energy production during the year (tilted around 27° to the north) (Zomer *et al*., 2016).

Figure 1. PV systems at Lab. Fotovoltaica-UFSC, Sapiens Parque.

1.2 Electric Bus (e-Bus)

The UFSC e-Bus is totally powered by the PV systems installed in the Lab. Fotovoltaica-UFSC, at Sapiens Parque, Florianópolis-SC. It started to operate regularly in March 2017, and, since then, the 26-km route from the laboratory to the UFSC main campus has been monitored under real traffic conditions. The e-Bus carries out five 52-km trips (2 x 26 km each trip) per day and ran over 40,000 km by November 2017.

In total, there are 38 passenger seats and two conference tables with 220 V sockets and USB-ports to enable a working environment during the 30-minutes trip. After every 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 founded by the Ministry of Science, Technology and Innovation (MCTI, currently MCTIC) together with the partnership of the companies WEG, Eletra, Marcopolo and Mercedes-Benz.

The vehicle has a bodywork from Marcopolo, which was already available in the market (Torino Low Entry). It offers an access ramp for people with special needs and provides extra wide seats as well. The chassis is the electric 0500U of Mercedes-Benz and the electric motor is a WEG three-phase 250 L with 200/400 kW of power. The electric integration project was developed by Eletra and has a set of eight Li-Ion battery packs, with a total of 128 kWh of capacity.

2. METHOD

In order to meet the aims of this article, the following steps were followed:

1. Analysis of monthly generation of the Lab. Fotovoltaica-UFSC grid-connected PV systems;
2. Analysis of the monthly e-Bus consumption;
3. Performance of the e-Bus and estimation of selected influencing factors on the consumption of the e-Bus during a trip;
4. Monthly comparison between the PV generation and the e-Bus consumption.

2.1 Analysis of monthly generation of the Lab. Fotovoltaica-UFSC grid-connected PV systems

The measurement of the monthly generation of the Lab. Fotovoltaica-UFSC grid-connected PV systems was performed with the data acquisition from the inverters. The analysis is performed for one year (November of 2016 to October of 2017) of operation of the PV systems, in order to obtain data of all seasons. The PV system on the roof of the e-Bus recharge station has no data for 2016, because it was installed at the end of December/2016. In total, 92.14 kWp of PV panels installed are considered in this analysis. The monthly yield of the systems was calculated by dividing the generation (in kWh/month) by the functional installed capacity (kWp).

2.2 Analysis of the monthly e-Bus grid consumption

On 06/03/2017, the e-Bus began operating with five daily 52-km trips (Sapiens > UFSC > Sapiens). Since 20/03/2017 every recharge at Sapiens Parque has been monitored with the inbuilt electricity meter in the recharge station. The values of energy consumption were monitored at each recharge and then multiplied with the efficiency loss of the charging station and then summarized to the monthly grid consumption. The charging station has a measured efficiency of 87.3%.

Eq. (1) shows the calculation of the monthly e-Bus grid consumption.

$$GridConsumptionBus_{Monthly\_i}=\sum_{d=1}^{n} ConsumptionBus_{Daily_i}(d)*\frac{1}{\eta_{Charging\_station}} \quad (1)$$

Where:
$GridConsumptionBus_{Monthly\_i}$ is the monthly e-Bus consumption [kWh], from the grid, for the month "*i*";
$ConsumptionBus_{Daily_i}(d)$ is the daily e-Bus consumption [kWh], from the charger, over day "*d*" for the month "*i*";
n is the number of days of month "*i*", and
$\eta_{Charging\_station}$ is the efficiency of the charging station.

Survey of the e-Bus round trips consumption. The following variables are being monitored throughout the trips: average speed (with stops), consumption and braking regeneration. The information gets monitored trough a data logger, which is connected to the WEG inverter of the engine. During the trip, to estimate the e-Bus consumption, there is access only to the SOC (State of Charge) data from the BMS (Battery Management System).

To keep the survey more accurate, only trips without air conditioning were analyzed. A more accurate estimation of the consumption during the whole trip can be achieved through monitoring the electricity consumption during the recharges. To minimize errors, the bus is in charging mode and components such as light, air conditioning and hydraulic bomb are turned off.

Eq. (2) shows the calculation of the e-Bus consumption during a round trip.

$$ConsumptionBus(\Delta s)=\left(\frac{SOC_o}{100}\cdot J_{Battery}\right)-\left(\frac{SOC_s}{100}\cdot J_{Battery}\right) \quad (2)$$

Where:
$ConsumptionBus(\Delta s)$ is the e-Bus consumption [kWh], from the battery, during a round trip at distance "*s*";
SOC_o is the battery state of charge at the beginning of the trip [dimensionless, zero corresponds to 0% and 100 corresponds to 100%];
SOC_s is the battery state of charge at distance "*s*" [dimensionless, zero corresponds to 0% and 100 corresponds to 100%], and
$J_{Battery}$ is the total energy (nominal) that can be stored in the e-Bus battery bank [128 kWh].

Eq. (3) shows the calculation of the e-Bus consumption [kWh], from the charger, during a round trip.

$$ConsumptionBus_{Trip}=J_{charge}+\left[\frac{(SOC_o-SOC_{After\_charge})}{100}\cdot J_{Battery}\right] \quad (3)$$

Where:
$ConsumptionBus_{Trip}$ is the e-Bus consumption [kWh], from the charger, during a round trip;
J_{charge} is the total e-Bus consumption [kWh] during the recharge (as indicated in the 75-kW charger display);
SOC_o is the state of charge of the battery at the beginning of the trip [dimensionless, zero corresponds to 0% and 100 corresponds to 100%];
SOC_{After_charge} is the state of charge of the battery after recharging [dimensionless, zero corresponds to 0% and 100 corresponds to 100%], and
$J_{Battery}$ is the total energy (nominal) that can be stored in the e-Bus battery bank [128 kWh].

2.3 Performance of the e-Bus

Since 18/07/2017, every trip was monitored with a data logger from WEG, which is mainly taking his information from the inverter for the engine. The sample rate is 1 Hz and monitors the input/output of the inverter, depending if the engine is acting as generator or as a motor.

Eq. (4) shows the calculation of the total engine consumption calculated with the efficiencies of the inverter, the battery and the BMS, presented in Tab.1. The positive values are measured at the output of the inverter, so efficiency levels from inverter, battery and BMS have to be considered in the calculation. The negative values are measured at the input of the inverter, so only efficiency levels from battery and BMS have to be considered in the calculation.

Table 1 – Efficiency Levels of parts of the eBus for total consumption calculations.

Efficiency Levels	
BMS	93.31%
Battery	92.00%
Inverter	95.00%
Positive Values (BMS, Battery and Inverter)	81.55%
Negative Values (BMS and Battery)	85.85%

$$\text{totalConsumption}_{\text{Engine}} = \frac{\int_{t=0}^{t_{end}}[(J_P(t)>0)*\eta_{\text{Positive\_values}} + (J_P(t)<0)*\eta_{\text{Negative\_values}}]}{3{,}600\ \text{sec}} \tag{4}$$

Where:
$\text{totalConsumption}_{\text{Engine}}$ is the total engine consumption [kWh], from the battery, during a round trip;
J_P is the power of the engine at the instant "t" (positive values when accelerating and negative values when braking) [kW];
$\eta_{\text{Positive\_values}}$ is the efficiency for the positive values (BMS, Battery and Inverter);
$\eta_{\text{Negative\_values}}$ is the efficiency for the negative values (BMS and Battery);
t is the time interval from the beginning of the trip [sec], and
t_{end} is the time when the trip ends [sec].

Survey of the comparison between average velocity and engine consumption. This survey is pointing out that the major consumption in the e-Bus is the engine. However, the efficiency of the engine is changing trough different operation conditions (e.g. average velocity, passenger load).

An important value with a big influence is the average velocity, because the efficiency of the engine decreases the most, when leaving its standard working point of 1,200 rpm (≈ 39 km/h) or when a high number of stop-and-go occur during the trip. So, engine consumption (without regenerative braking) and avg. Velocity (with stops) were compared against each other.

Eq. (5) shows the calculation of the average e-Bus velocity during a round trip.

$$\text{avg. Velocity} = \frac{\sum_{t=0}^{t_{end}} v(t)}{N} \tag{5}$$

Where:
avg. Velocity is the average velocity of the e-Bus during a round trip [km/h];
v is the instantaneous velocity at the instant "t" [km/h];
t is the time interval from the beginning of the trip [sec];
t_{end} is the time when the trip ends [sec], and
N is the number of records of instantaneous velocity, throughout the round trip.

Survey of the comparison between passenger load and engine consumption. To research the impact of different passenger loads during round trips, the number of passenger was monitored throughout 40 trips. The number of passengers was then compared to the engine consumption without considering regenerative braking, to have a more accurate result.

2.4 Monthly comparison between the PV generation and the consumption of the e-Bus

With the obtained data in previous surveys, a comparison was made to verify how much of the generated energy trough PV systems at Lab. Fotovoltaica UFSC was used for the e-Bus recharging. The analysis is performed only for the months when the e-Bus was operating regularly (March to October of 2017).

3. RESULTS

All the results of the different surveys of the e-Bus are presented in this chapter.

3.1 Analysis of monthly generation of the grid-connected PV systems of the Lab. Fotovoltaica-UFSC

Tab. 2 presents the data obtained for the total generation of the Lab. Fotovoltaica-UFSC PV systems. Most of the power is produced by the PV system on the roof of Building A.

The generation of the ground systems varies over the months not only because of the seasonal variations of solar irradiance, but also because these systems are used for training and research purposes. Therefore, they are often disconnected.

The months with less generation were May and June, explained by the low irradiance in the city of Florianópolis. In addition, February and March are months with low PV production even being months with high irradiation. That is explained by a technical problem in one of the inverters of the PV system of building A, which was soon replaced.

The Lab. Fotovoltaica-UFSC PV systems have generated more than 100 MWh, during the considered period. That means a production of 1,098.5 kWh/kWp/year, which is very high considering that most of the installed power are not in the position for optimizing the production. As a reference, an ideally tilted and oriented flat PV system installed at UFSC yielded 1,265 kWh/kWp over a 12 months period (Urbanetz *et al.*, 2011). Even though the two systems have been operating for different periods and the gathered data refer to different years; it is valid to note the Lab. Fotovoltaica-UFSC generated 87% of an optimized system.

Table 2 - Monthly generation of the PV systems of Lab. Fotovoltaica-UFSC.

Month/Year	Energy generation [kWh]	Yield [kWh/kWp]
November/2016	9,536.1	106.3
December/2016	11,004.8	122.7
January/2017	11,983.8	130.1
February/2017	7,607.6	82.6
March/2017	7,577.8	82.2
April/2017	7,972.5	86.5
May/2017	4,858.6	52.7
June/2017	5,448.8	59.1
July/2017	8,196.1	89.0
August/2017	7,943.3	86.2
September/2017	8,473.5	92.0
October/2017	10,055.9	109.1
Average	8,388.2	91.0
Total	**100,658.8**	**1,098.5**

3.2 Analysis of the monthly e-Bus energy consumption

Tab. 3 shows the monthly e-Bus energy consumption. It is visible that in March/2017 the e-Bus has made less trips, since it was the first month of operation. Then, excluding this month, the average consumption of the e-Bus is 5,265 kWh per month. This results in a consumption of 1.13 kWh/km with an average transportation of 6 passengers (excluding driver). When considering the efficiency of the charging process, the energy consumption rises to 1.27 kWh/km. It is important to note that the e-Bus has a significant consumption, needing more than 39 MWh of energy to operate for 8 months.

Table 3 - Monthly consumption of the e-Bus

Month/Year	Consumption [kWh]	Number of Charges	Consumption per Trip [kWh/Trip]	Distance Travelled [km]
March/2017	2,514.6	43	58.48	4,009
April/2017	4,930.9	85	58.01	4,421
May/2017	5,990.6	106	56.52	5,560
June/2017	5,517.2	97	56.88	5,093
July/2017	4,998.3	83	60.22	4,606
August/2017	4,816.3	84	57.34	4,438
September/2017	5,178.6	90	57.54	4,681
October/2017	5,425.9	90	60.29	4,678
Average (March/2017 was excluded for the calculation of average consumption and of average consumption per trip)	5,265	84.75	58.11	4,686
Total	**39,372.4**	**678**	**-**	**37,486**

3.3 Performance of the e-Bus

The following analysis and interpretations present the most important data of the survey, which were presented in subsection 2.3.

Analysis of the e-Bus energy consumption along a single trip. Fig. 2 shows the e-Bus energy consumption, estimated with the SOC variation (ΔSOC) along each single trip, considering ΔSOC equal zero at the beginning of each single trip. An increased slope of ΔSOC curve in Fig. 2 means that the bus is exposed to higher work load. In the other hand, when the bus is exposed to less load, the slope of ΔSOC curve in Fig. 2 decreases. If the ΔSOC gets lower than its previous values, we observe regenerative braking that charges the battery.

When looking closer at the fast increase/decrease of ΔSOC at Δs = 19 km when driving from Sapiens Parque to UFSC and Δs = 6 km when driving from UFSC to Sapiens, we see the exact same location. The elevation profile of the path between Sapiens Parque and UFSC is presented in yellow in the graphs. It is visible the clear relation between the increased energy consumption/production to the elevation profile of the path, being the e-Bus exposed to higher workload when facing elevations on the road. When the vehicle goes down the elevations, the driver breaks, and energy is regenerated charging the battery.

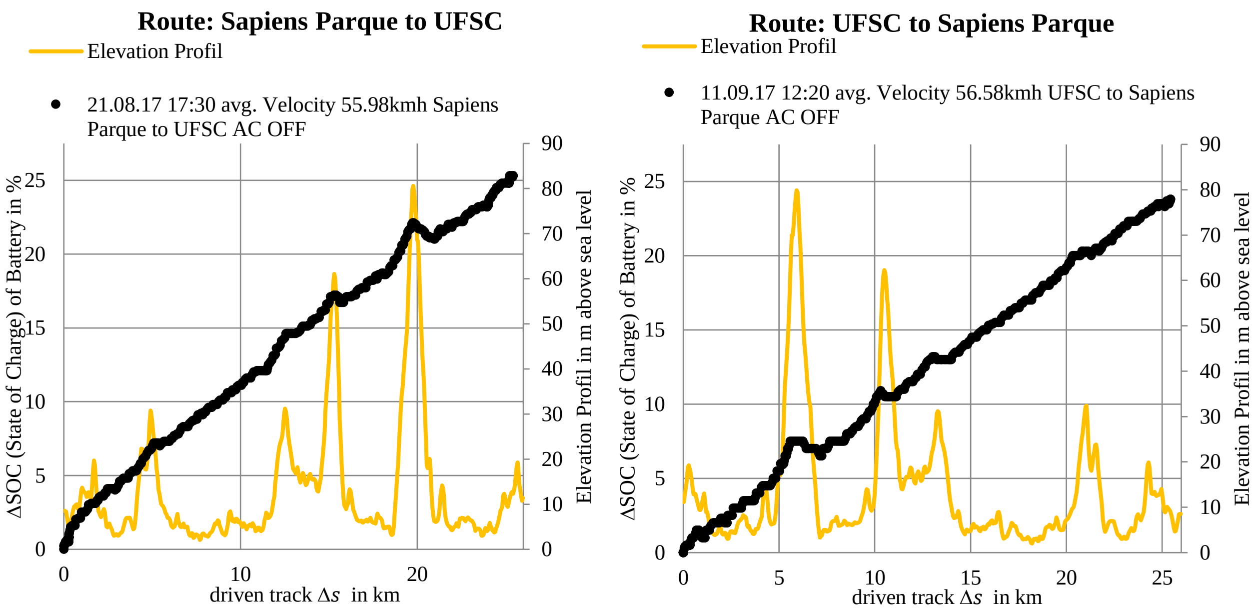

Figure 2 - Monitoring discharge of battery against elevation profile of single trips.

Analysis of comparison between average velocity and engine consumption. The Fig. 3 shows a monitored series (Serie1) of 40 round trips, which took place at 11:50 AM and 05:30 PM. The x-axis shows the average travelling speed (including stops) and the y-axis the estimated engine consumption from the battery, without the regenerative braking. The trend line is linear and shows connection between engine consumption and average velocity.

Analysis of the comparison between passenger load and engine consumption. The Fig. 4 shows a monitored series of 40 round trips, which took place at 11:50 AM and 05:30 PM. They are separated in two groups with similar travel speed. The graph shows little dependence between consumption and passenger load. This can be explained by the small weight difference generated by the passengers, when considering the bus weight of over 16 tons.

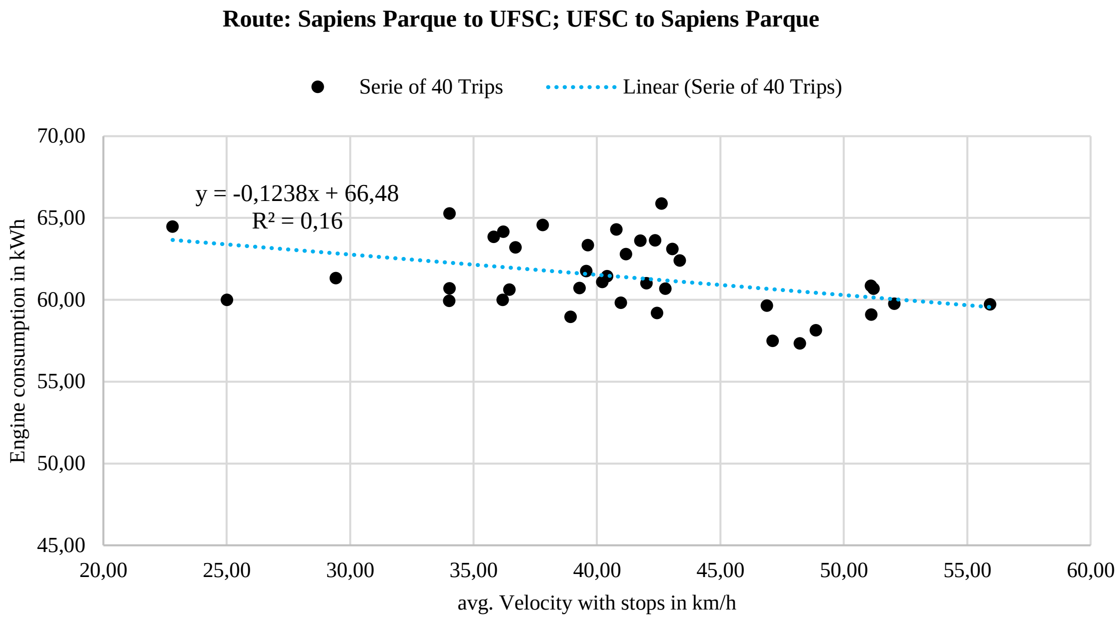

Figure 3 - Monitoring round trips (Sapiens Parque to UFSC to Sapiens Parque).

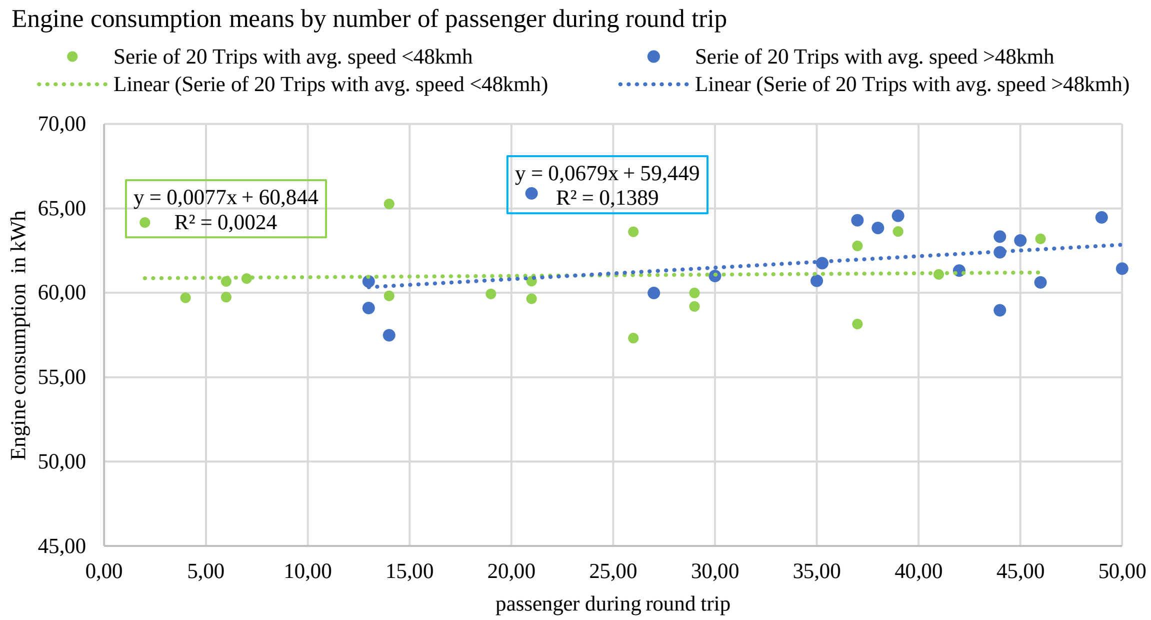

Figure 4 - Monitoring the consumption of the engine with different passenger loads. The results are separated in two groups of over 48 km/h and under 48 km/h average travel speed.

3.4 Monthly and annual comparison between the PV generation and the consumption of the e-Bus

Tab. 4 shows the results of the comparison between the PV generation of the Lab. Fotovoltaica-UFSC and the e-Bus energy consumption during the period that it operated regularly (March/2017 to October/2017). An important conclusion from the data is that in most of the months, the PV production of the laboratory surpass the e-Bus energy consumption. The months that there is not enough energy production to supply the e-Bus energy consumption are only May and June, which are months with low irradiance in Florianópolis. In addition, May was the month that the e-Bus made more trips, justifying its high energy consumption.

Despite these two months, in the sum of all the period analyzed, the bus only represented 75% of the PV energy production of the Lab. Fotovoltaica-UFSC.

Table 4 – Comparison between the PV generation and the consumption of the e-Bus.

Month	**PV generation [kWh/month]**	**Consumption e-Bus [kWh]**	**Percentage of the PV generation used for the e-Bus [%]**
March	7,577.8	2,877.6	38%
April	7,972.5	5,645.6	71%
May	4,858.6	6,858.9	141%
June	5,448.8	6,318.4	116%
July	8,196.1	5,707.0	70%
August	7,943.3	5,514.4	69%
September	8,473.5	5,993.5	71%
October	10,055.9	6,210.4	62%
Total	**60,526.5**	**45,125.9**	**75%**

4. CONCLUSION

The analysis showed that in the period of one year, the PV systems installed in the laboratory generated more than 100 MWh, with a productivity of 1,098 kWh/kWp/month, which is high for Florianópolis, considering that the most of the PV modules are not in optimized orientation/slope. It also showed that the e-Bus has a high energy consumption, having consumed more than 45 MWh from the grid in 37,486 km travelled.

In addition, many conclusions about the e-Bus consumption were reached. The results suggest that the most influencing factor of the discharge during a trip is the average speed, which can be explained by the increased consumption of the engine. On the other hand, the influence of the passenger's load on the discharge of the battery is very little, explained trough the small weight difference between passenger's load and the weight of the e-bus. Also, the regenerative braking system restores up to 20.2% back to the battery packs of the used energy for the engine and extends the autonomy up to 25%.

The data gathered in this study also indicates that during the period of regular operation of the e-Bus, its consumption only represented 75% of the PV energy production of the Lab. Fotovoltaica-UFSC, meaning that the vehicle is totally powered by solar energy.

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