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Benefit Analysis of Grid Connected Photovoltaic Solar System with Energy Storage

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HIGHLIGHTS

- Commissioning of Grid connected photovoltaic Solar System with Energy storage in Curitiba.
- Storage energy with lead-acid batteries in Brazil.
- Bidirectional inverters.
- Energy Time Shift.

Abstract: The use of batteries combined with photovoltaic (PV) systems connected to the grid allows the storage of surplus energy from photovoltaic generation for later use. This combination can reduce dependence on the grid, since, for most consumers, peak consumption does not occur simultaneously with peak generation from the PV system. This article describes the initial operation of a PV system with 10.72kWp connected to grid and associated to a storage system with 57.6kWh lead-acid batteries installed at the Federal University of Technology - Paraná, in Curitiba city, Campus Neoville. We present an analysis of the benefits obtained from the combined use of the PV system connected to the grid with energy storage, reducing the total energy consumed from the grid. A brief analysis of the demand showed that, for this UTFPR campus, the peak power consumption occurred between 10:00 and 12:00 AM, which was also the interval of peak photovoltaic generation. We have observed that a scheduled battery discharge of 5.5% of the storage capacity from May to November and 9% discharge in December has resulted in R$ 1,154.44 of saving in the first seven months of operation.

Keywords: Grid Connected Photovoltaic System; energy storage; energy management strategies.

INTRODUCTION

The search for solutions to meet the requirements of demand, reliability and sustainability resulted in the deployment of a large number of renewable sources such as distributed PV, wind and concentrated solar power. Currently, about 27.3% of the world electricity mix is represented by renewable sources [6]. The Brazilian energy mix is mostly composed of renewable sources, and photovoltaic represents 1.94% of the total [1]. Photovoltaic energy is intermittent by nature, since it varies spatially and temporally. Power production occurs only during the hours of the day and in addition, its peak generation occurs at a different interval than the peak consumer demand. Additionally, variations in generation resulting from weather changes can cause fluctuations in voltage and reactive power, and consequently changes in the power quality indexes.

Since the applications of these systems are quite diverse, the possibility of managing demand and generation using photovoltaic systems connected to the grid with associated battery storage becomes a viable solution to achieve goals such as: the displacement of the load curve during peak hours, provision of ancillary services, among others.

Different energy storage systems have different characteristics and are generally classified based on the rated discharge duration time [5]. The discharge duration of long-term storage systems, such as energy storage systems with pumped hydrogen or compressed air, varies from several hours to days, but their applications are restricted by low response speeds. Batteries, which are the medium-term storage devices most used in power systems [3], can discharge for several minutes to hours. Short-term storage devices, such as steering wheels and supercapacitors, have extremely high response speeds, but they can only discharge for an instant, so that they can satisfy power demands quickly, but only for short periods of time.

The use of photovoltaic generation complemented by storage systems has been presented as an important trend for the electric sector in the future, which may result in benefits for consumers and the sector.

The distributed generation photovoltaic system integrated with the storage system is still scarcely present in the Brazilian scenario, most of the facilities and works in the area are still in their initial stages.

For [4], who used the HOMER software to make simulations, with a 30.36 kWp system with a storage system composed of 20 stationary lead acid batteries with a capacity of 220Ah totaling 52.8 kWh in storage capacity. The batteries discharged for 38 minutes at peak hours between 6:00 and 9:00 PM to service the load, charge off-peak when the tariff is the lowest, have storage losses of the order of 20%, have output energy of 2717 kWh/year, which represents a monthly savings of R$ 360.00, annual savings of R$ 4,320.00 and a total savings of R$ 27,618.00 until the end of its life cycle.

The Federal University of Santa Maria is developing the same bidirectional inverter from the NHS, for residential environments using artificial intelligence methods and concepts of Internet of Things to manage residential lighting loads and HVAC systems. Monitored residential environmental data, power generation and status of battery management system are used in the decision-making process, the institution's research has two patent filing procedures in progress.

This paper aims to present the installation phases of the pilot project and the preliminary results of the operation of a 10.72 kWp photovoltaic system with energy storage of 57.6 kWh to contribute to demand control during peak hours, discharging about 5.5% and 9% of the energy storage system and this does not include a feasibility analysis, or rate of return, as some equipment was donated to the university and others acquired through a research and development project.

MATERIAL AND METHODS

The storage systems integrated with Photovoltaic Systems Connected to the Network in Brazil is still a technology under development, its implementation is still restricted, as the Brazilian legislation is in the process of being elaborated.

Some institutions with support from research and development funds, have implemented small photovoltaic systems connected to the grid with storage to study their applications and benefits, among them University of São Paulo (USP), LACTEC, Federal University Technological of Paraná (UTFPR) among others.

The service voltage of the university consumer unit is 13.8kV three-phase, with an installed load of 100kW, Group A and green fare.

To develop the energy management strategy, we have collected energy demand data since 2019 through the local electricity company. With the collection of daily demand data. Figure 1 shows this monthly curve, where it is possible to see the demand surpassing.

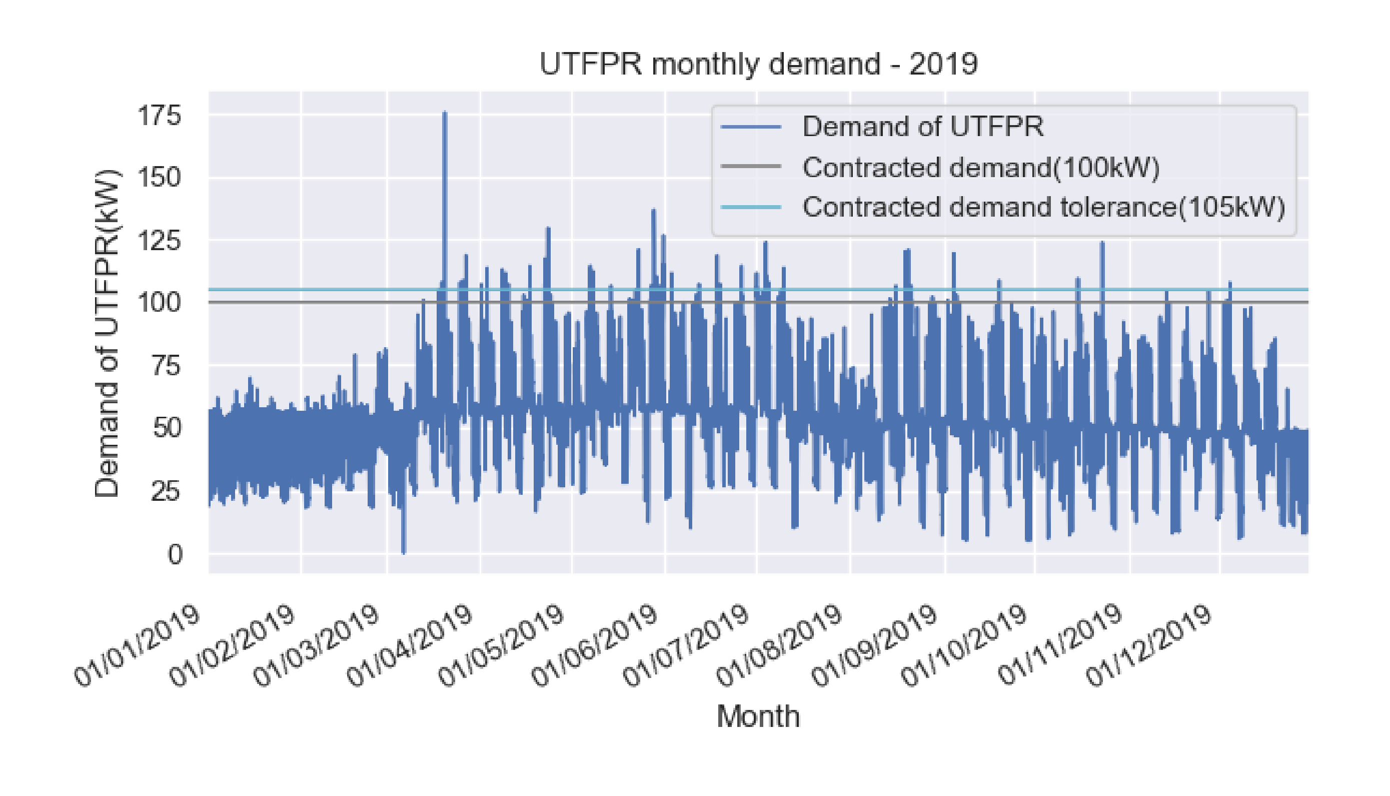


Figure 1. UTFPR Campus Neoville building demand chart 2019.

With frequency analysis, we found that the periods that present the greatest demand are between 10:00 and 12:00 AM, and in these periods occurs the demand surpass shown in Figure 1. During the months of December, January and February, the university has typically a low demand, since this corresponds to a period of recess.

In Figure 2, we present a period of 3 days, from March 18th to 21st, where it is possible to visualize the surpass of demand between 10:00 and 12:00 AM, precisely the period in which the peak generation of photovoltaic systems occurs.

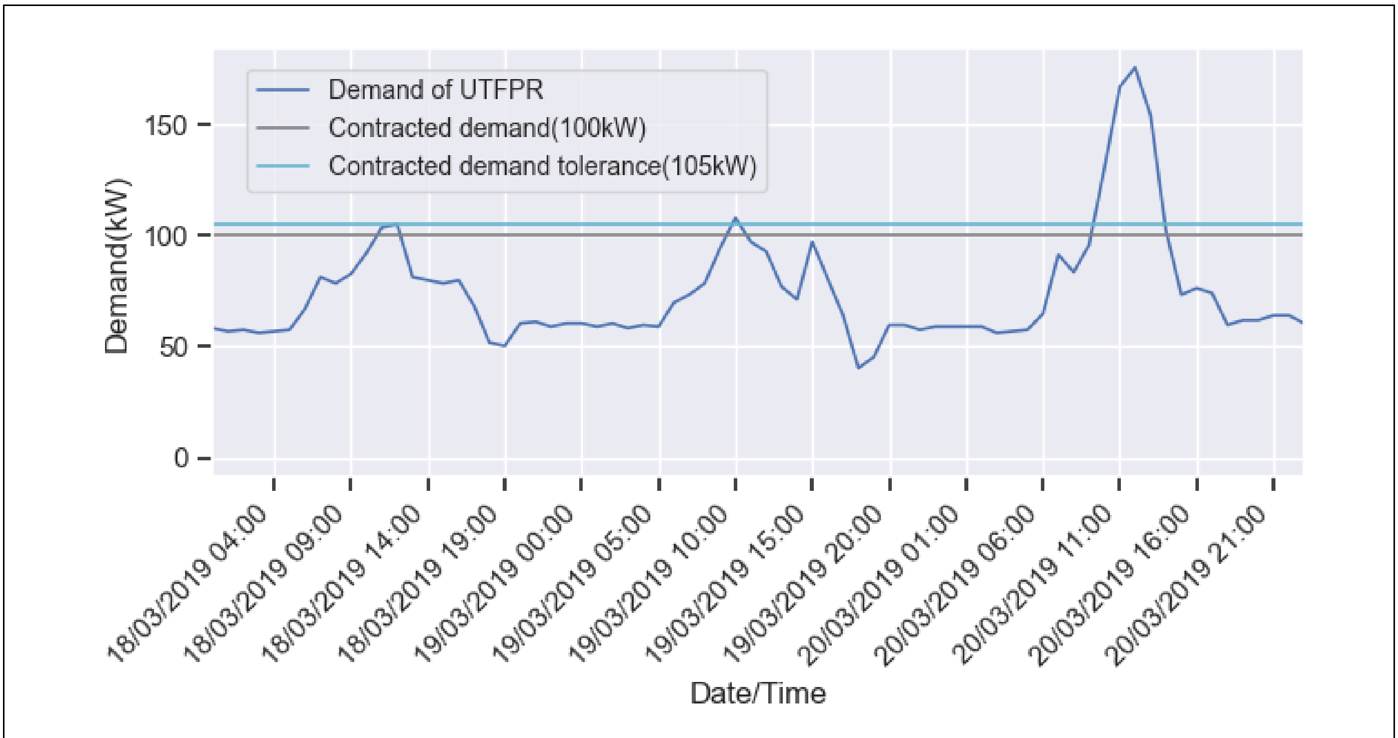


Figure 2. School business day demand march 18 to 21/2019.

For the implementation, some studies were carried out, one of them using SketchUp software to make shading analysis in the best and worst scenarios throughout the day and the seasons, to define the best installation position and angle of the modules inclination.

The calculation of the projected monthly and annual energy generation was performed applying the irradiation data in the tilted plane angle (25º) from the Atlas of Paraná Solar Energy database (Table 1) [8]. Having obtained the daily average monthly irradiation values in the PV tilted angle, it is estimated the average daily electricity generation through Equation (1) [9].

Table 1. Irradiation data (kWh/m2.day) [8].

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5.4	5.15	4.53	3.77	3.07	2.75	2.89	3.87	3.86	4.43	5.26	5.61

$$E = \frac{Pfv.Htot.PR}{G} \quad (1)$$

Where: E: average daily electricity (Wh/day); Pfv: photovoltaic power installed (Wp); Htot: monthly average daily solar irradiation for the locality in question (Wh/m².day); PR: Performance Rate or Performance Ratio, typically between 70 and 80% (80% for this analysis); G: irradiance in the Standard Test Conditions (1,000 W/m²). Figure 3 shows the calculated results of the monthly and annual projected generation PV-battery system generation in 2020.

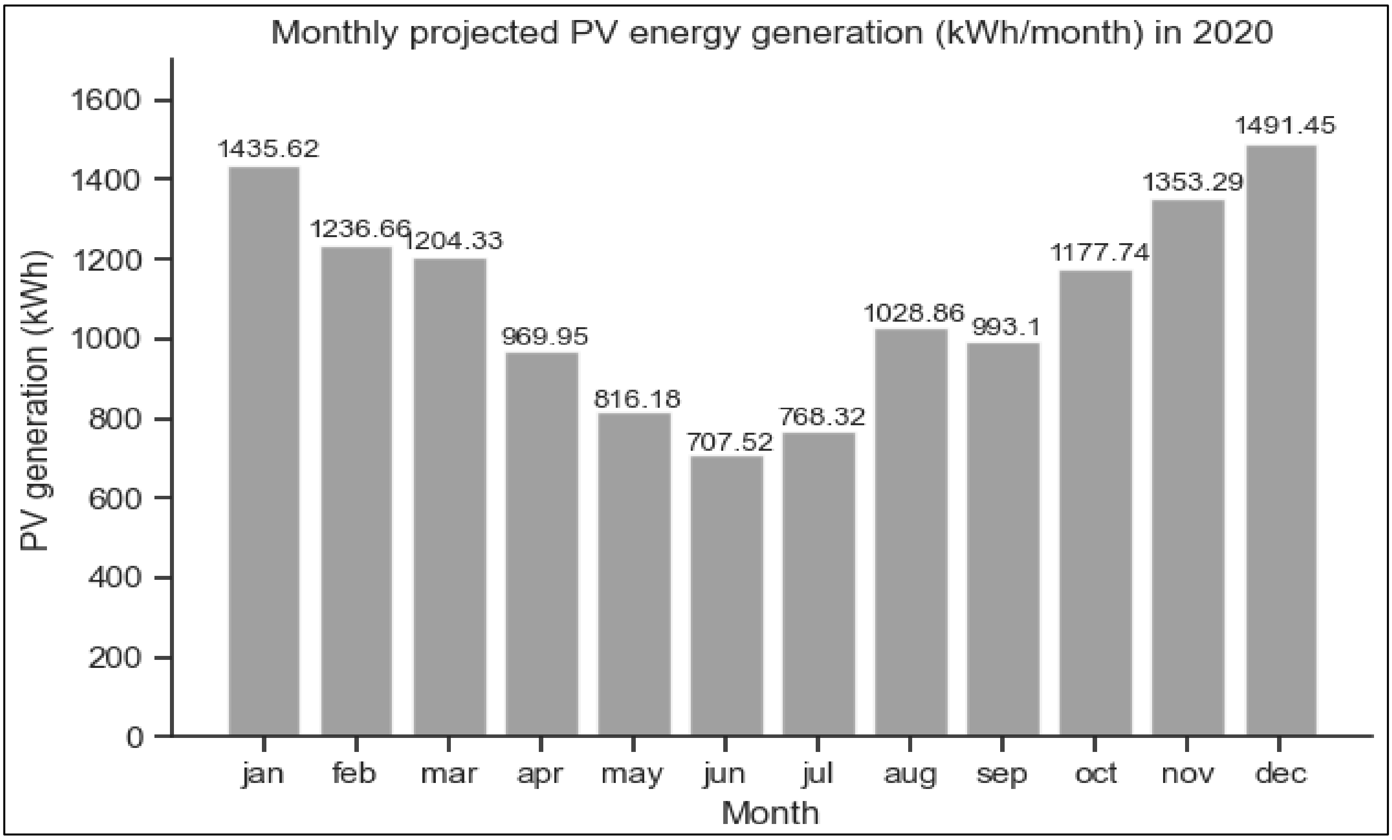


Figure 3. Monthly and annual projected generation PV-battery system generation in 2020

After the preliminary studies for the pilot project were concluded, the geographical area and the best geographical position for installation were defined. The works for the implementation of the system started on 02/20/2019 and the equipment was acquired with P&D resources 2866-0464/2017- Methodology for Analysis, Monitoring and Management of the distributed energy through encouraged sources from COPEL Distribution.

The equipment were installed in an area of approximately 636m², measuring 30.00m wide and 21.20m long. The system consists of: 32 units of polycrystalline silicon photovoltaic modules, having 335Wp each, from manufacturer Qcells, totaling 10.72kWp; two bidirectional inverters NHS 5kW; and a battery bank for energy storage consisting of 80 stationary batteries of the type DF 1000 lead-acid from manufacturer Heliar, totaling 57.6kWh in storage capacity. The geographic coordinates of the site are: 25.50° latitude, 49.32 longitude and zero azimuth deviation. Figure 4, provides a detailed view of the system and the rated power of each of the devices displayed.

The load of the UTFPR is composed of the sum of the power from the grid, the battery and the PV system (Equation 2).

$$pgrid + pac + pbat = put, \quad (2)$$

Where,
pgrid - Power from the grid.
pac – Power from Photovoltaic (alternating current – ac)generation in output of inverter.
pbat – Power from energy storage system.
put – Load power requirement from university.

The university's load is always greater than the photovoltaic production, therefore the energy produced by the photovoltaic system is totally consumed by the institution.

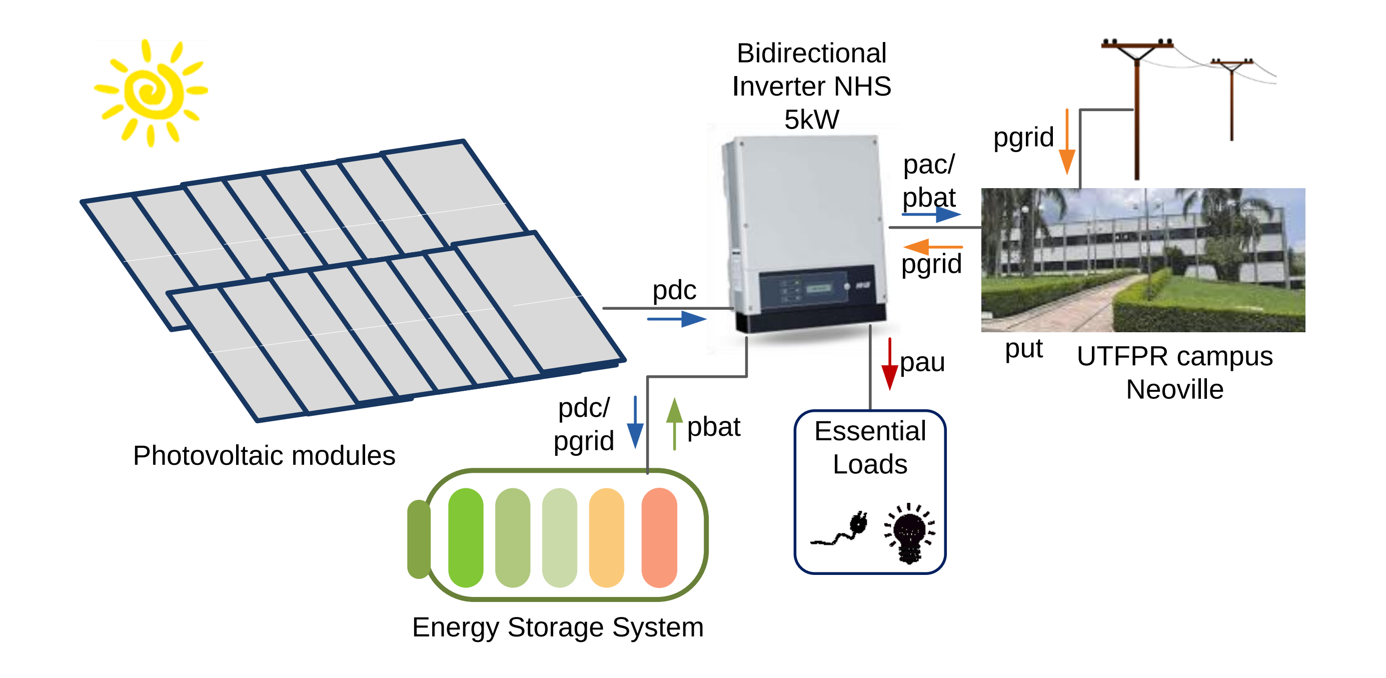


Figure 4. Overview of the grid connected PV system with storage at UTFPR.

Where:
pgrid - Power from the grid.
pdc – Power from the PV generation (direct current).
pac – Power from Photovoltaic (alternating current – ac) generation in output of inverter.
pbat – Power from energy storage system.
put – Load power requirement from university.
pau – Power required from essential loads.

For the storage system start-up period, we defined that 5.5% of the daily storage capacity would be discharged during the peak period (6:00-9:00 PM), a constant discharge during 3 hours of 3kWh and we left the inverter configured with the factory setup to start charging the batteries from main power after the completion of the programmed discharge.

In June, the inverters were configured to charge the batteries using photovoltaic generation and in the absence of this charge using main power.

This UTFPR pilot project aims to demonstrate the interaction between generation, demand and charging of batteries and the benefits in the application of energy management strategies such as Energy Time Shift among others. Configuration was made in the inverter program that does not allow the user to use 100% of the energy stored in the batteries in order to protect the equipment. The moderate energy discharge values of the storage system has been calculated to preserve the integrity of the bank of lead-acid batteries, which are designed to have a service life of around 4 years with a discharge depth of 20% at 25°C.

Commissioning of Solar Photovoltaic System with Energy Storage at UTFPR

The first stage of the project consisted in the preparation of the area for the equipment installation. The suppression of vegetation in the topsoil was carried out, afterwards the territory was delimited and marked at the corresponding distances for each row of PV modules. Next, the concrete structures were built for the installation of the structures supporting the components, as shown in Figure 5 (a). Following this step, a layer of perforated plastic tarpaulin was installed to prevent the proliferation of weeds, and a layer of 5cm gravel number 2 was placed, as shown in Figure 5 (b). Finally, the galvanized steel supports were placed, with variable height from the ground, following the unevenness of the terrain, and facing north at an angle equal to the latitude of Curitiba, which is 25 degrees, as shown in Figure 5 (b).

(a) (b)

Figure 5. (a) Preparation of the boxes for concreting the foundation and **(b)** installation of the supports for the metallic structures.

After the installation of the structures, 32 polycrystalline silicon photovoltaic modules from the manufacturer Qcells, with 335Wp each were installed, totaling 10.72 kWp. The modules were placed in 4 parallel rows with 8 modules per row, and each row with a string box for protection installed in the metal structure. Therefore each row of 8 modules forms a string connected to the bidirectional inverter. Figure 6 (a) shows the start of the modules placement, while Figure 6 (b) shown the complete work.

(a) (b)

Figure 6. (a) Beginning of installation of 335Wp modules; (**b)** End of installation of the modules.

To install the bidirectional inverters and the battery banks that make up the system, a shelter measuring 2.00 x 2.00 x 2.20 m (width x length x height) was built in concrete blocks, with natural ventilation and with an access door of 0.80 m, as shown in Figure 7.

Figure 7. Housing for inverters and batteries.

In this housing, the following equipment were installed: the two bidirectional inverters of 5kW each, from the manufacturer NHS; the storage system composed of 80 elements of stationary lead-acid batteries model DF1000 60Ah-12V from the manufacturer Heliar Freedom, totaling 57.6kWh in capacity of energy storage. The batteries were installed in four racks, where each rack contains 20 batteries connected in series, performing 240V. Each pair or racks is connected in parallel to each of the bidirectional inverters, as shown in Figure 8.

Figure 8. NHS 5kW inverters and Heliar DF 1000 batteries installed in the housing.

Figure 9 shows an overview of the Grid connected Photovoltaic System of 10.72kWp with energy storage system at UTFPR .

Figure 9. Grid connected Photovoltaic System with energy storage system at UTFPR Campus Neoville.

There are several energy management strategies, for the study the energy time shift is being used and a scenario for peak shaving will be simulated.

Energy Time-shift

Electric energy time-shift involves purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the stored energy can be used or sold at a later time when the price or costs are high. Alternatively, storage can provide similar time-shift duty by storing excess energy production, which would otherwise be curtailed, from renewable sources such as wind or photovoltaic (PV) [2].

In Figure 10, a scheme of one of the energy time shift strategies is presented, during the period of the peak, comprising an interval of three consecutive hours from 6:00 PM to 9:00 PM during the week, the discharge of 5.5% of the 57.6kWh of the storage system, representing about 3kWh of energy injected and consumed by the university.

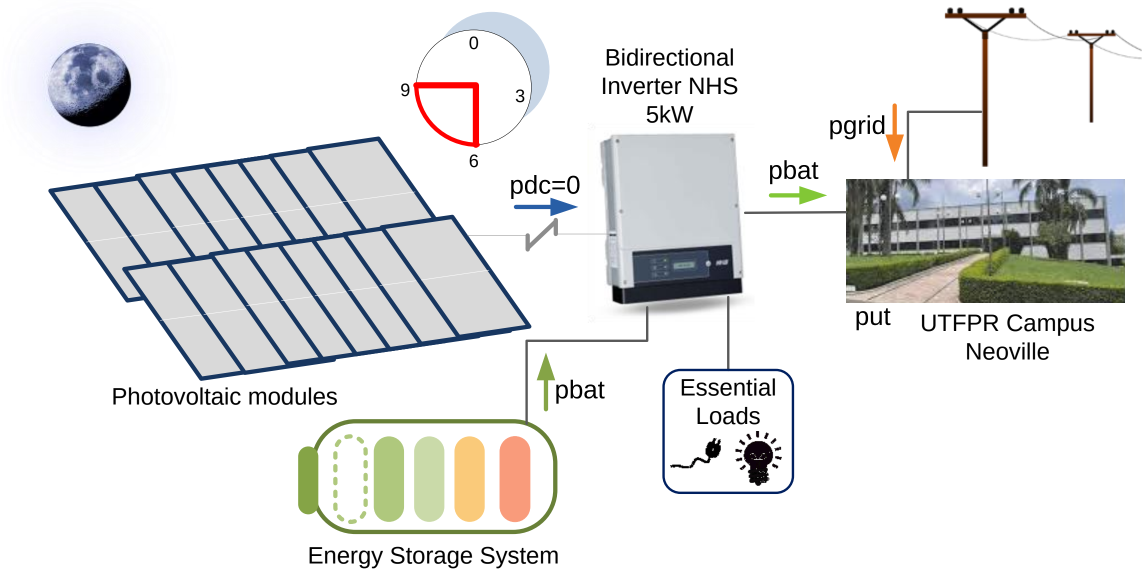


Figure 10. Scheme energy time shift in the week.

In May 2020, we started to collect the first results of the pilot project, using the programmed injection of 0.5kW per hour of power during the peak, shown in Figure 11.

At peak hour (6:00-9:00 PM) is discharged at constant power, monitoring voltages and currents of the batteries, state of charge and implementing the counting of the number of charging/discharging cycles. Figure

11 shows a typical cycle of 24 hours from May 18th to 19th, 2020. The cycle consists in the following periods: (1) a PV generation period, from 7:00 AM to 6:00 PM, where the peak generation is 4.24kW; (2) a scheduled discharge period, from 6:00 to 9:00 PM; (3) a battery charging period, after 9:00 PM.

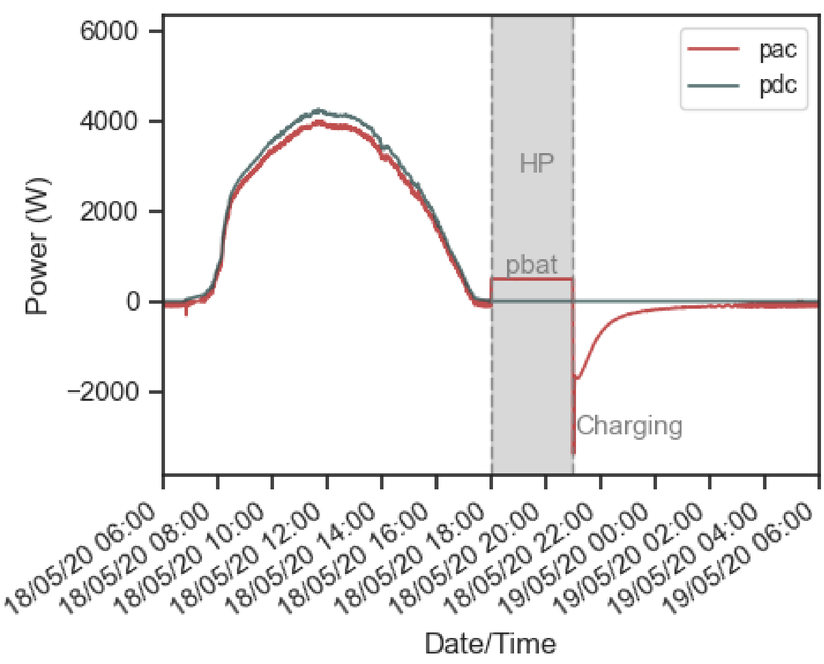
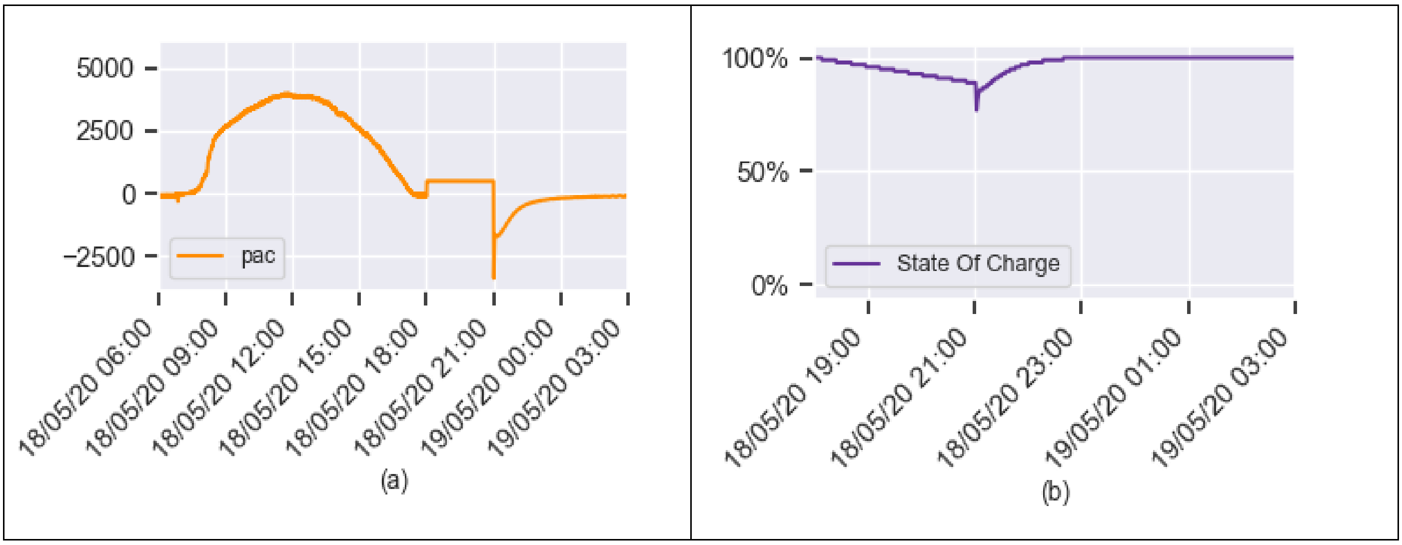


Figure 11. Typical curve, photovoltaic generation, discharge and charge the batteries of the bidirectional Inverter 1.

Where:
pdc – Power from the PV generation (direct current).
pac – Power in output of inverter (alternating current).
pbat – Power constant from storage system.
HP – Peak demand, these hours are typically from 18h - 21h during weekdays.

At the beginning of the operation of the system, the batteries were charged primarily with grid power, immediately after the end of the scheduled discharge. The process is performed automatically by the inverter, which disconnects the batteries and starts charging the batteries causing a peak in power consumption from the grid. Figure 11 shows a negative peak of 3.38kW right after the discharge ends and the charging process begins. Figure 12 (a) shows the power measured at the inverter's output; 12 (b) shows the percentage of charge held at the batteries; (c) and (d) show the discharge/charge current and voltage from the batteries during the cycle.



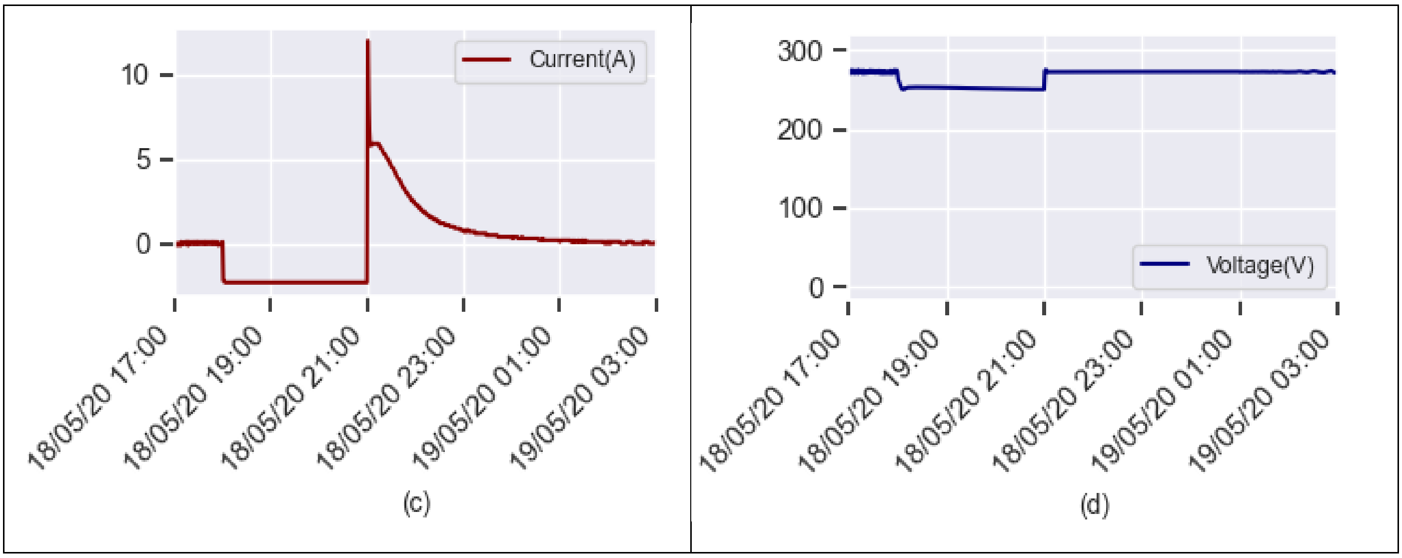


Figure 12. Behavior of PV system with storage during bank discharge a)Power in the output inverter. b) State of charge. c) Current during discharge. d) Voltage during discharge.

In June 2020 a scheme was implemented in the inverters for giving priority to charge the batteries from the PV generation. Figure 13 shows in blue the PV generation (direct current) and in red the output power (alternating current) of the inverter. At 9:00 AM the charging process starts with peak of 1,48kW negative required from PV generation.

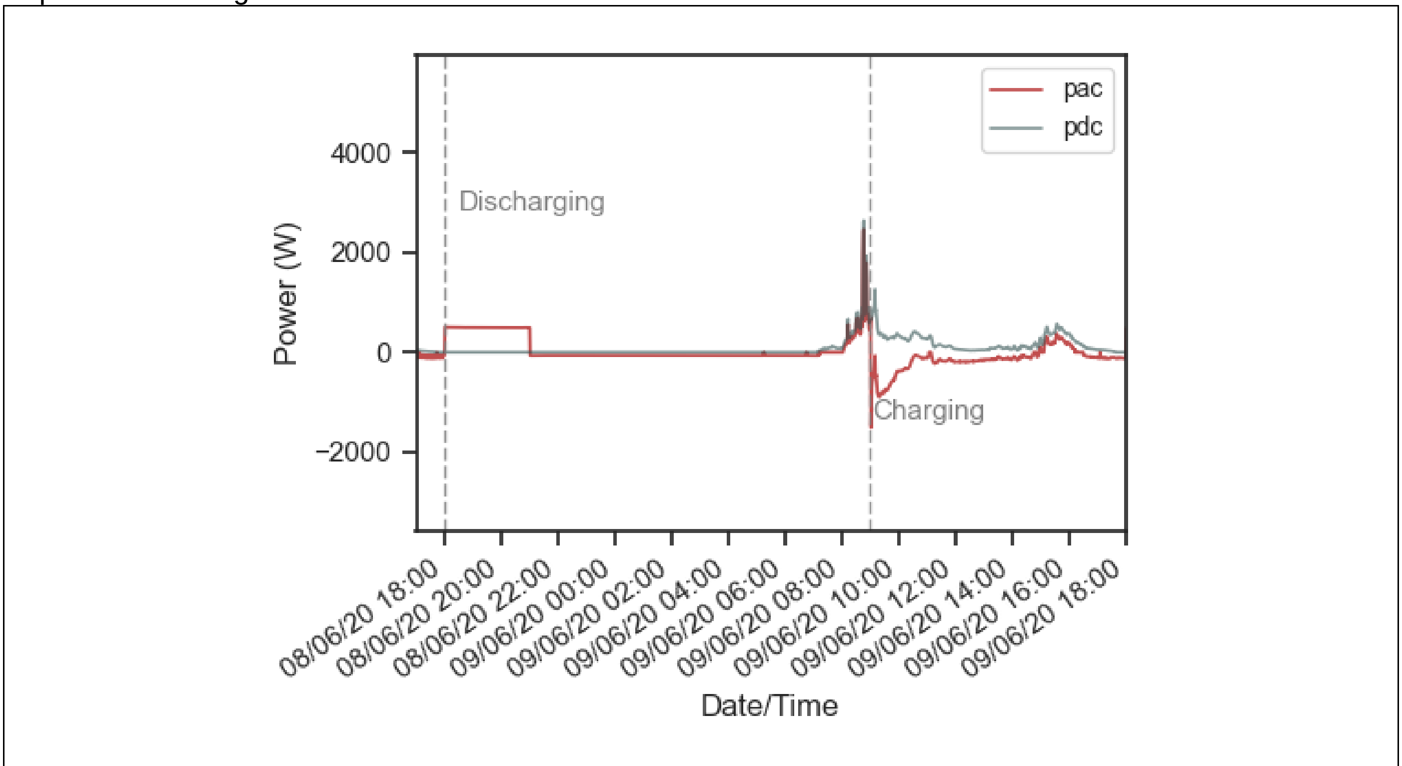


Figure 13. Charging the energy storage system with photovoltaic generation.

Where,
pdc – Power from the PV generation (direct current).
pac – Power in output of inverter (alternating current).

In December 2020, as shown in Figure 14, the discharging of 1kW per inverter during the peak hours. The curve in red shows the power in the output of the inverter, with negative peak occurring at 9:00 AM, corresponding to the start of the battery charging cycle, which takes 9 hours to complete.

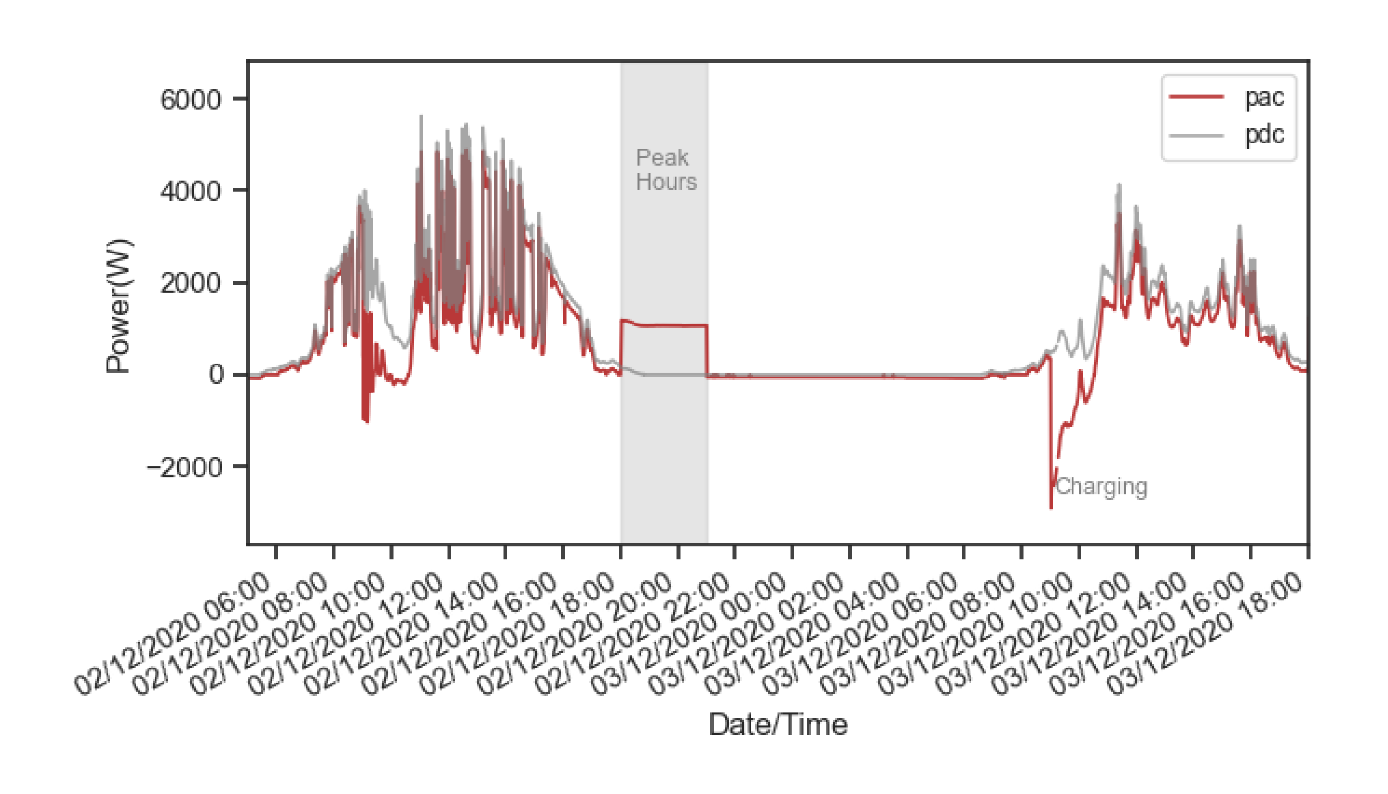


Figure 14. Discharging of 1kW in the peak hours.

RESULTS

The commissioned pilot project has shown satisfactory results in the first 8 months of operation. Figure 15 presents a comparison with the projection of energy generation of the system and the real observed values. The year 2020 was an unusual year, having a long drought period, with more sunny days and consequently higher PV production, particularly from May to July.

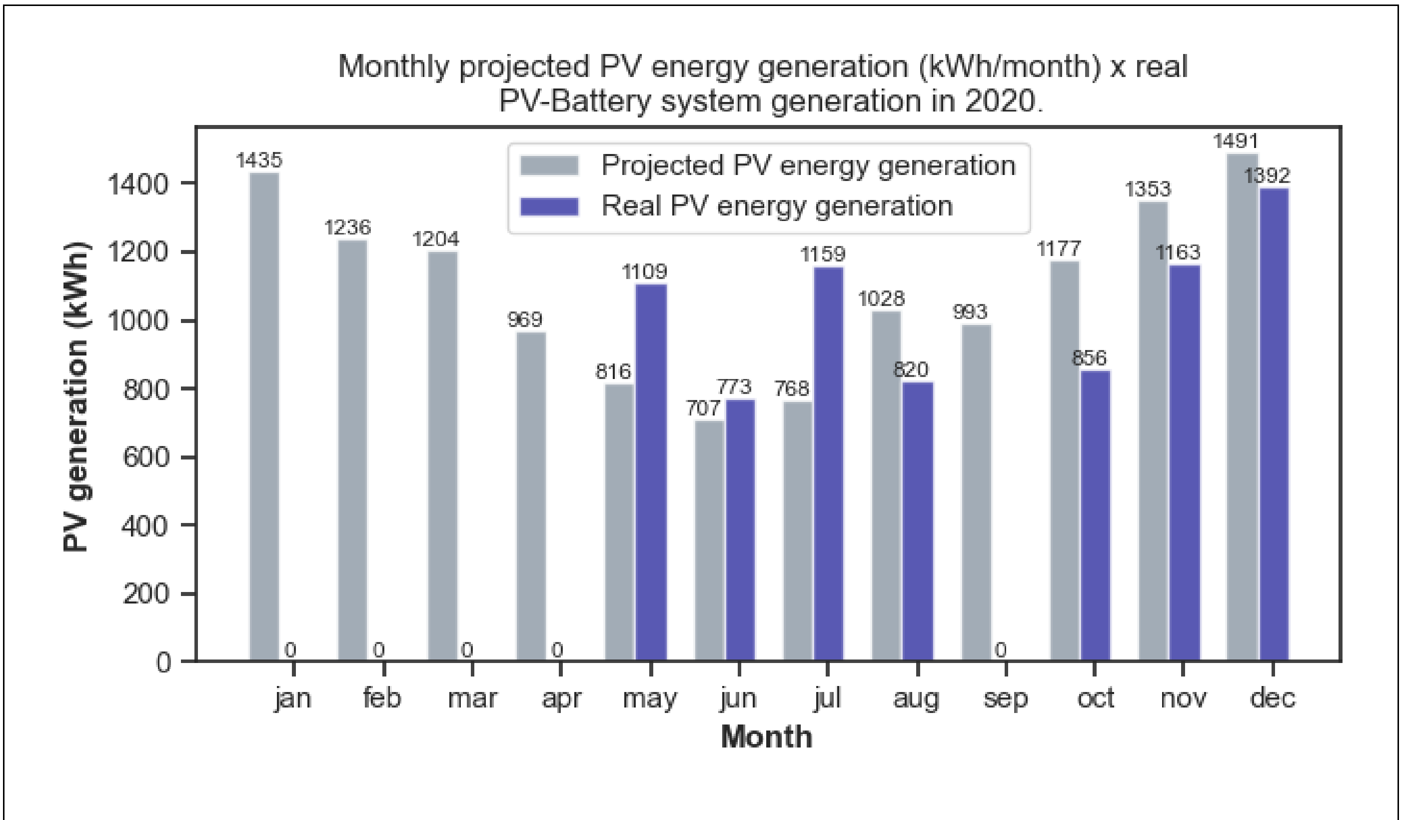


Figure 15. Monthly projected PV energy generation (kWh/month) and the real PV-Battery system generation in 2020.

Figure 16 shows the monthly discharged energy from the storage system. The data corresponding to September/2020 have been lost due to a network problem. In December/2020 the scheduled discharges of the storage system resulted in 198.46kWh.

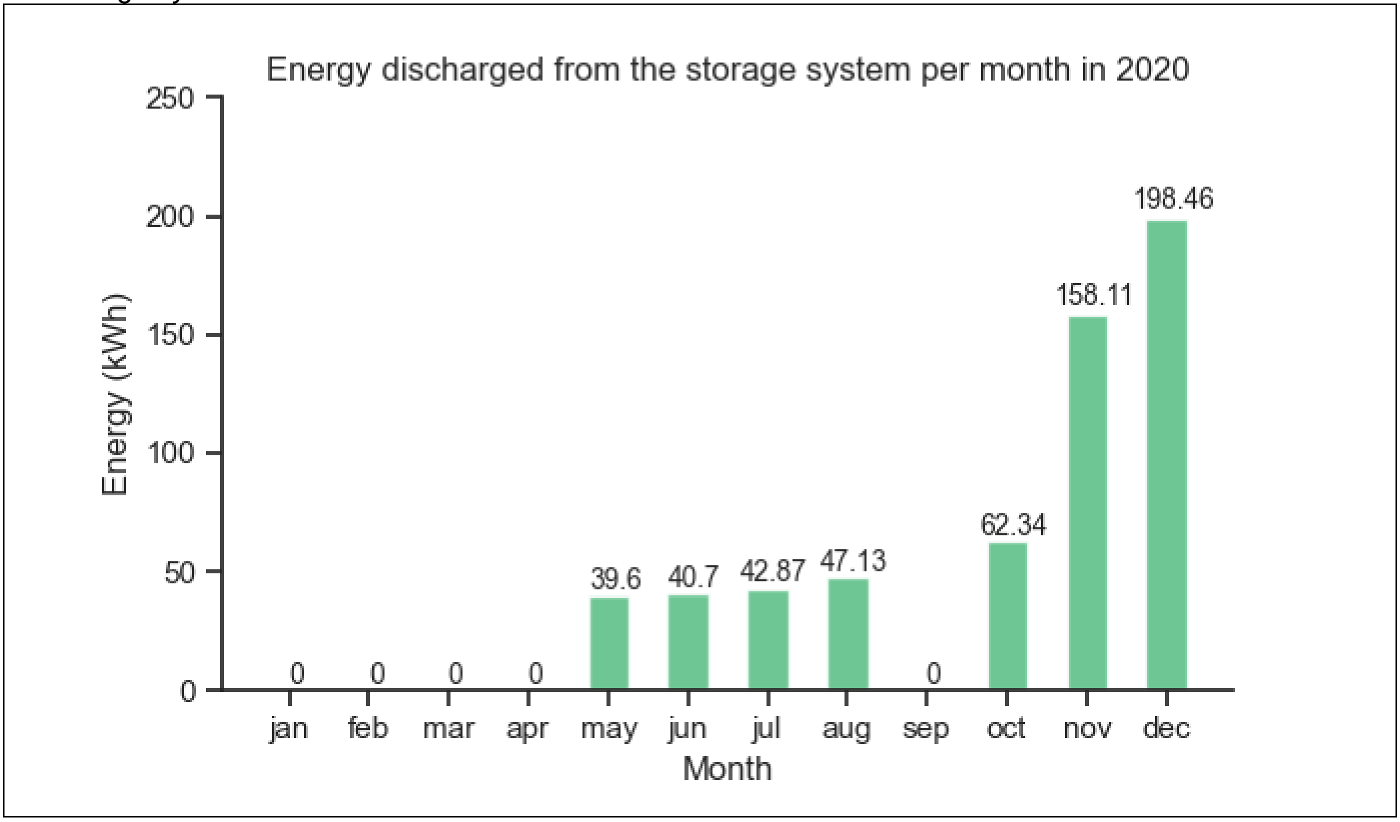


Figure 16. Energy discharged per month in 2020 of energy storage system of 57.6kWh.

The profile of charge and discharge of the batteries, the number of cycles and discharge depth are determinant factors of the device's life cycle, which is typically four years if correctly operated. Figure 17 shows the battery discharge curve as a variation of the battery's voltage as a function of time, for a given constant discharge current. If either the discharge current or the discharge time are increased, the voltage tends to decrease even further. When charging starts, a voltage and current peak occurs, and afterwards the voltage remains constant until the batteries are completely charged. Once charged, the voltage fluctuates around 275V and the current becomes approximately zero. The charging cycle shown in this image took five hours.

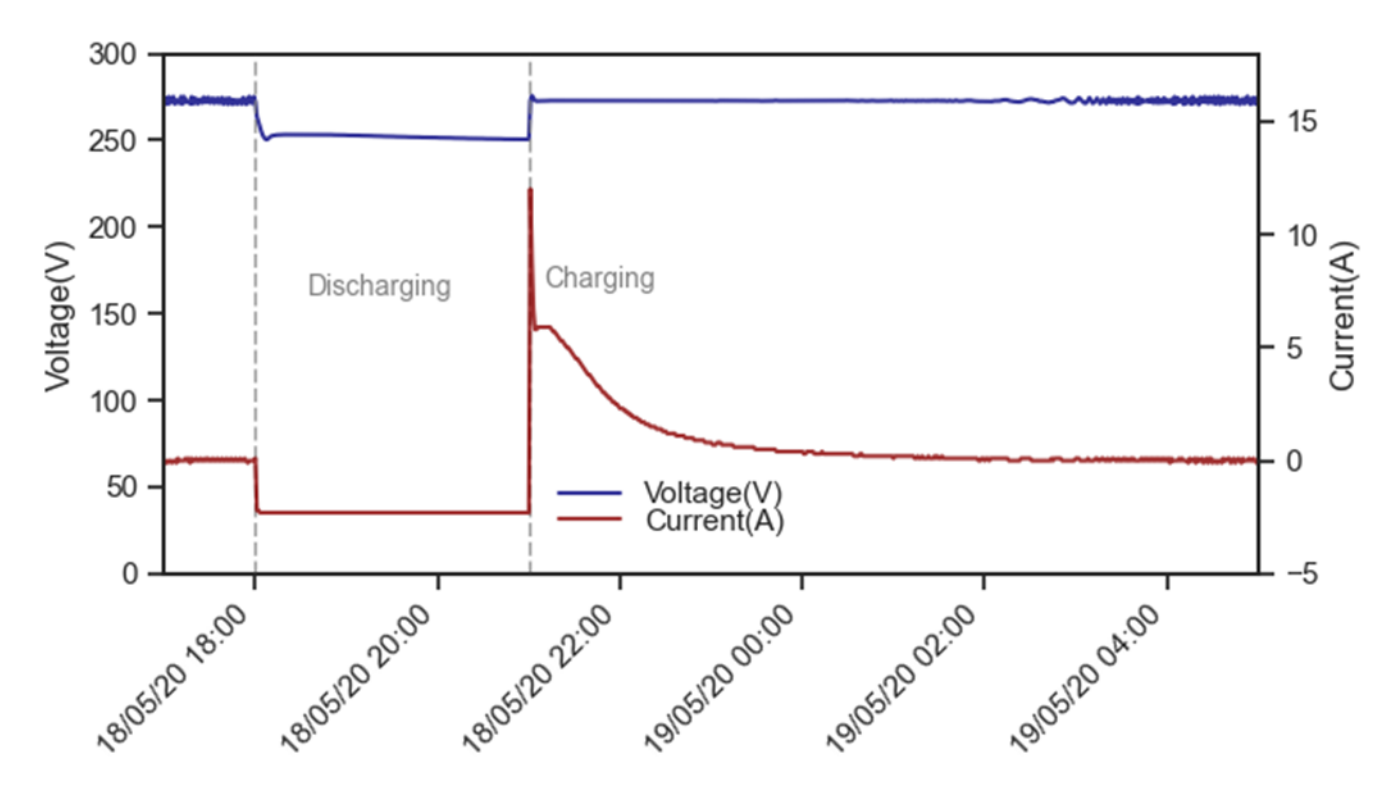


Figure 17. Batteries charging, curves Voltage and Current.

Using the PV power production data associated with the battery discharge data we performed a monthly analysis of consumption in the peak hour with 3kWh daily battery discharge and off peak consumption with photovoltaic generation, as shown in Figures 18 and 19.

The combined operation of PV and energy storage systems in the case analyzed demonstrates the interaction between generation and demand, offering a certain level of autonomy to the energy consumer. The PV generation reduced, in average, 2.7% the monthly power consumption, while the energy storage system was able to reduce the peak consumptions in 1.6% average.

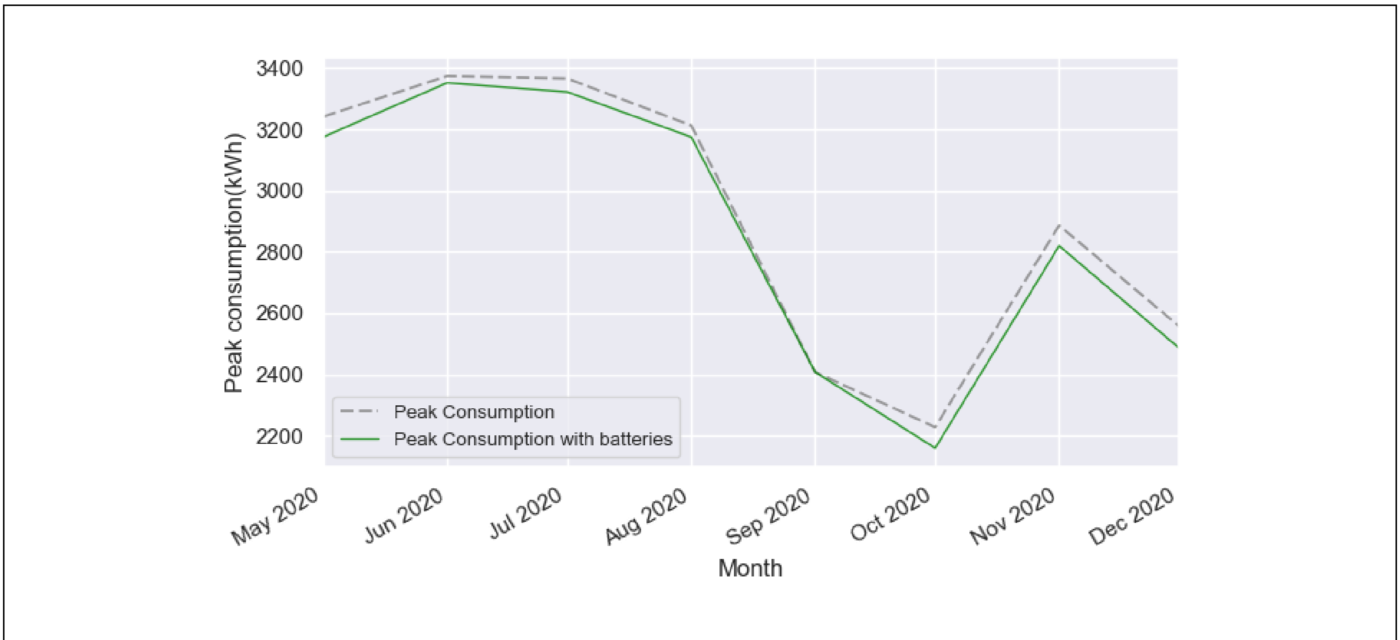


Figure 18. Peak consumption and peak consumption with battery discharge in seven months of operation.

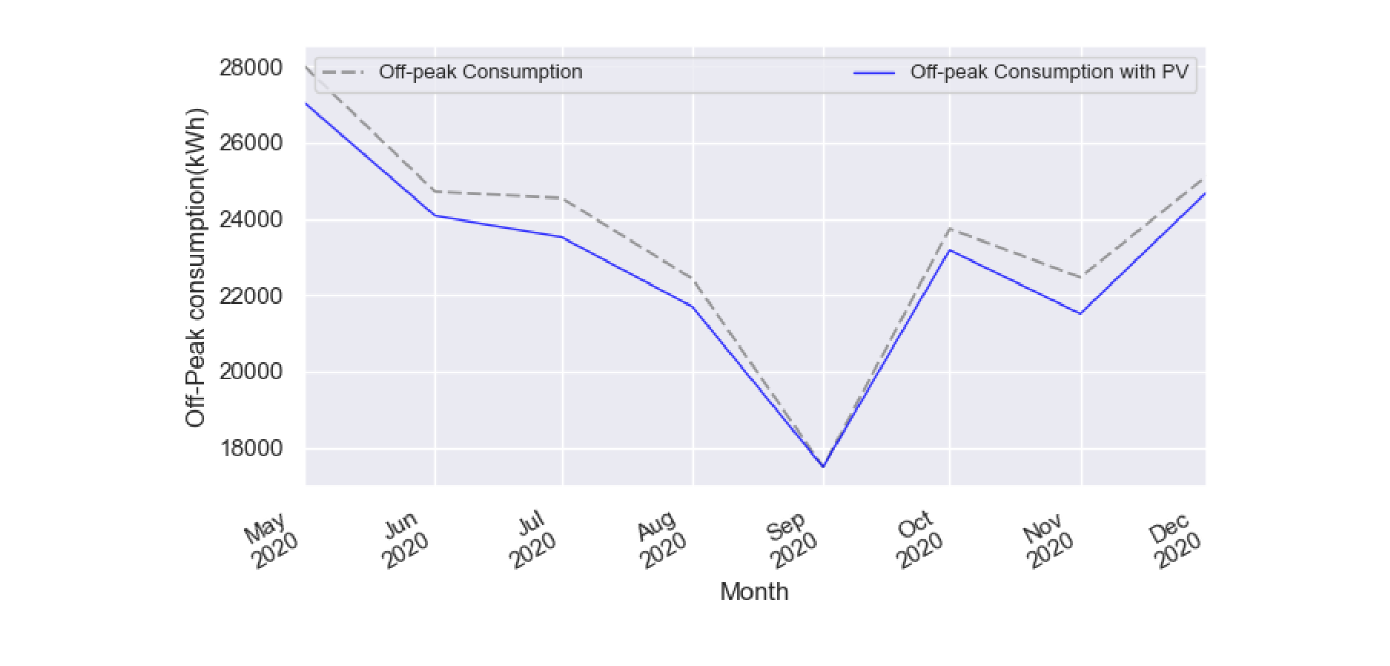


Figure 19. Off-peak consumption and off-peak consumption with PV generation in seven months of operation.

In December the difference in off peak consumption with the addition of photovoltaic generation is more accentuated in the blue line, since the days are longer in the southern hemisphere, therefore having more photovoltaic generation.

DISCUSSION

Electricity customers usually have an uneven load profile during the day, resulting in load peaks. The power system has to be dimensioned for that peak load while during other periods of the day it is under-utilized. The extra costs in keeping up with the peak demand are passed to the customers in form of a power fee, i.e. you pay for your maximum peak load [7].

By utilizing an Energy Storage System (ESS), peak load can be reduced and hence the power fee. The ESS is controlled to charge up during off-peak hours and discharged during peak hours.

Figure 20 shows the combined data in one day-analysis comprising the building demand (gray), demand with PV generation (blue), demand with PV generation and battery bank discharge (green). The contracted demand supplied by the electricity company on the delivery bus is 100kW (continuous line) with a 5% tolerance off-peak, i.e., 105kW (dashed line).

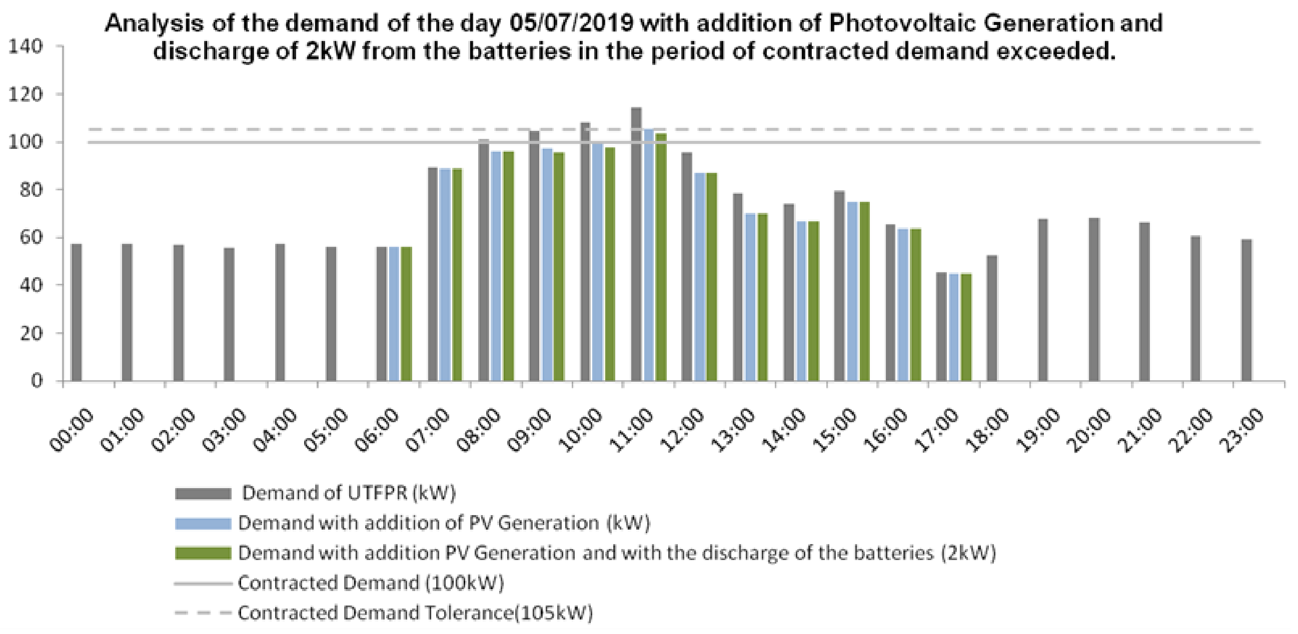


Figure 20. Simulation of peak shaving at UTFPR with 1kW per inverter during the hours from 9:00 to 11:00 AM.

CONCLUSION

By analyzing the available data corresponding to seven months of the PV system's operation, we have observed a total of 7.275 MWh power production, which is satisfactory compared to the expected generation of 7.340 MWh for that period. This amount of energy, produced at the off-peak hours and considering a price of R$ 0.69 per kWh, results in saving R$ 5,020.24.

The total energy discharged from the batteries during this seven months period was 589kWh, always at the peak hours. Considering a price of R$ 1.96 per kWh at the peak hours, this amount of energy would be priced at R$ 1,154.44. The same amount of energy consumed at the off-peak hours to recharge the batteries, priced at R$ 0.69 per kWh, would cost R$406.41. Therefore, the savings resulting from the storage system would be roughly R$ 748.03 during the period under consideration.

The combined savings are relatively small, however other benefits are provided by the system, for instance: supply the essential loads during periods of disconnection from the grid and reduce the peak of demand, possibly reducing fees resulting from exceeding the agreed demand. Despite the slight rates of energy contribution, the study confirms the ability of renewable integration along with batteries to enable energy management in this building during peak hours.

The results obtained in the operation of the photovoltaic system integrated with the storage system were also useful to parameterize maximum and minimum values of battery charge and also voltage levels, so the batteries can operate safely at prolonged life cycle. These batteries are designed to operate for approximately 2500 cycles, and until December/2020 the energy storage system performed 106 such cycles, with regular discharges below 20% of the system's capacity, all discharges and loads are monitored precisely to identify any anomalies.

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