Proceedings of the 5th International Conference on Energy Harvesting, Storage, and Transfer (EHST'21)
~~Niagara Falls, Canada~~ Virtual Conference – May 21-23, 2021
Paper No. 112
DOI: 10.11159/ehst21.112

Battery Energy Storage System Integration in Photovoltaic Buildings: A Pilot Project in a Brazilian University

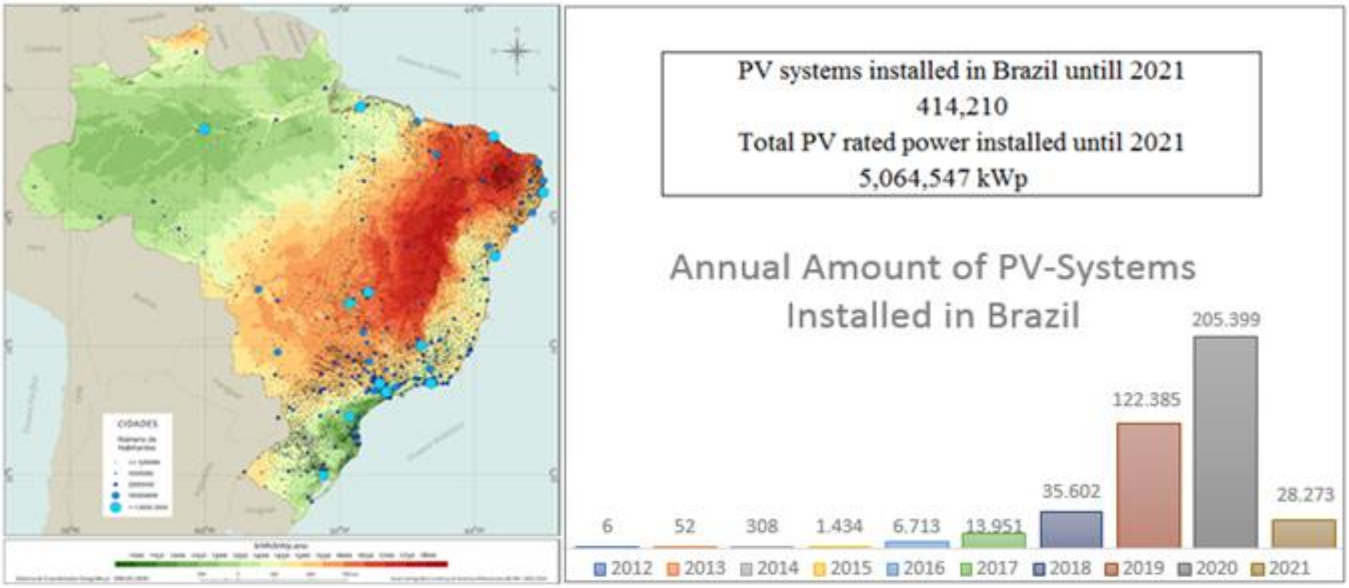
Juliana D'Angela Mariano[1], Adriana Schilive de Souza[1], Jair Urbanetz Junior[1]
[1]Federal University of Technology - Paraná
3165 Avenida Sete de Setembro, Curitiba, Brazil
julianamariano@alunos.utfpr.edu.br; adrianaschilive@alunos.utfpr.edu.br; urbanetz@utfpr.edu.br

Abstract **–** Photovoltaic-grid-tie systems (PV) have been widely applied in the urban buildings, as well as in a large-scale form in Brazil. Despite of its several advantages, the renewable energy source is variable and intermittent, where challenging its implementation. A possible solution is energy storage systems integration with renewable energy enabling energy management. The objective of the work is to describe the main phases of a pilot project for a 10kWp PV-battery-grid-tie-system in the city of Curitiba, Brazil, and highlight some preliminary results. The pilot project was installed in one of the Federal University of Technology – Paraná (UTFPR) campus in 2019, following the optimal operating conditions. Services, such peak-shaving; power backup; load-shifting; self-supply are expected with this project. The expectation of the system's annual electricity generation is 13.2MWh, however the first year of operation the PV-grid-tie systems presented its generation of 6.09MWh. This development can enable a scenario with lesser uncertainties regarding the variables and standardization of PV-battery-grid-tie systems operation in the urban environments.

Keywords**:** Energy Storage, Photovoltaic Systems, Pilot Project, Energy Management

1. Introduction

Photovoltaic-grid-tie systems (PV) have been massively installed along with residential consumers or in large-scale power plants in Brazil, due the country solar potential (Figure 1) [1, 2]. These systems present advantages in their application, such as low environmental impact, which can be considered as a versatile and powerful tool in achieving zero energy building demand [3]. However, its operation presents some challenges to be overcome, due to the variability and intermittency, requiring that there be planning of energy dispatch, making it challenging to implement [4].



(a) (b)

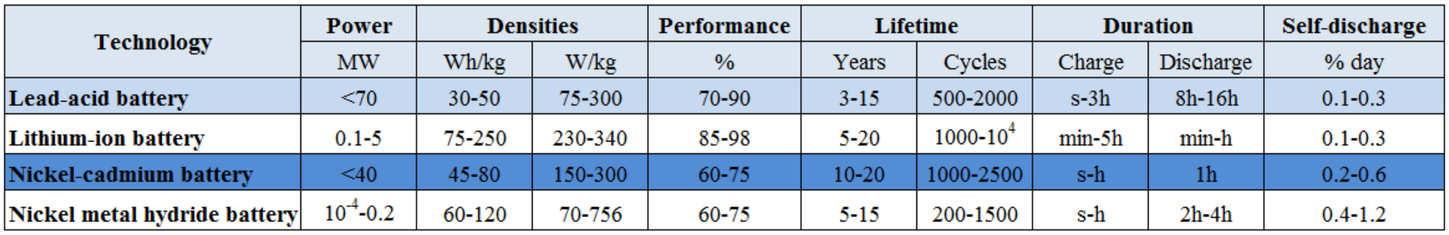
Fig. 1: (a) Solar irradiation potential and (b) annual PV-systems evolution in Brazil [1, 2].

According to [5] in the most countries worldwide, the PV-grid-tie maximum output power do not match with some consumer’s peak demand. Thus, energy storage systems integration with renewable energy can promote energy management during off-peak hours, when energy is cheaper, plus the battery discharge during peak demand. In addition, there is motivation for their combined use on price regulation tariffs.

The most widely used technology for energy storage renewable energy integration is the electrochemical batteries. According to [6] there is a wider range of commercially available, with each type being optimized for different purposes and applications. The integration of batteries along with PV-systems promote several benefits to consumers and the electric grid, due to their ability to maximize self-consumption of electricity generated by these systems. Moreover, these devices present maturity, costs, and discharge times for the period of minutes [7].

In addition, batteries are devices that give PV-systems greater flexibility, due to their ability to maximize the PV energy generation. Batteries are applied to operate close to their maximum power point track (MPPT), to supply electrical loads at stable voltages and to supply surge currents for electrical loads and inverters. There are two main classes of batteries primary and secondary. Primary batteries cannot be recharged and are not applicable in PV systems, consequently, secondary batteries can be recharged and, therefore, applied in PV systems. The most common types of batteries used in these systems are lead acid, lithium ions, nickel-metal-hydride, and nickel-cadmium (Table 1) [6, 8-10].

Table 1: Main characteristics of battery energy storage technologies (Lopes, 2015) [11].



Technology	Power	Densities		Performance	Lifetime		Duration		Self-discharge
	MW	Wh/kg	W/kg	%	Years	Cycles	Charge	Discharge	% day
Lead-acid battery	<70	30-50	75-300	70-90	3-15	500-2000	s-3h	8h-16h	0.1-0.3
Lithium-ion battery	0.1-5	75-250	230-340	85-98	5-20	$1000\text{-}10^4$	min-5h	min-h	0.1-0.3
Nickel-cadmium battery	<40	45-80	150-300	60-75	10-20	1000-2500	s-h	1h	0.2-0.6
Nickel metal hydride battery	$10^{-4}\text{-}0.2$	60-120	70-756	60-75	5-15	200-1500	s-h	2h-4h	0.4-1.2

As highlighted in Table 1, it is noted that lead-acid batteries have less storage capacity than lithium-ion batteries, higher density, and reduced service life, but lead-acid batteries are still widely used due to the advantages over other technologies, in terms of their low cost and improved maturity level, being more easily found for application [6, 12].

The Electricity Storage Handbook [13] describes some possible modes of operation for energy storage functionalities and their simultaneous uses such as: auxiliary services, transmission services, distribution services, massive energy system and consumer energy management. Regarding the integration of energy storage with renewable energies, it is possible to apply these last two categories mentioned, contemplating the following modes of operation: load shifting (time-shifting), peak demand reduction (peak-shaving), energy back-up, demand and consumption management and quality and reliability management. With these modes of operation, the PV system will be able to discharge its energy through energy storage for a period, such as during peak hours, at times when the fare is more expensive.

Within this context, the objective of the work is to describe the main phases of a pilot project for a 10kWp PV-battery-grid-tie-system in the city of Curitiba, Brazil, and highlight some preliminary results. The project under development also aims to analyse energy management strategies, using battery energy storage system.

2. Pilot Plant Phases

To increase the PV generation, the Solar Energy Laboratory (LABENS) of Federal University of Technology – Paraná (UTFPR) granted a research and development (R&D) project aiming to perform energy management. To achieve this goal, a PV-battery-grid-tie-system was installed as a pilot project, following the optimal operating conditions. In the southern hemisphere, these types of systems must follow some recommendations, such as PV panel tilt angle according to the latitude and oriented to the geographical north (latitude of -25,50º and longitude of -49,31º in this case of study). Besides the conditions mentioned, the system complies bidirectional inverters responsible to control and monitor electrical parameters. The described system was implemented in 2019 and aims to demonstrate several services, such as providing firm capacity in PV generation, peak-shaving; power backup; load-shifting; supply essential loads in isolated operation from the grid; voltage and frequency regulation and the reactive control of feeders.

The choice of the bidirectional inverter was based on the extensive review of the state of the art of storage systems in PV-buildings, and to look for the equipment that could meet the control of these smart grids in the context of smart buildings. This system requires certain equipment such as an inverter, a charge controller, and a battery bank management system, which is possible to find in a fully integrated version equipment. A survey was carried out at several equipment suppliers during national and international fairs as well as national manufacturers, where there were a few options available for application. During the equipment specification phase, there was a large offer of bidirectional inverters available for sale in the Brazilian market. Then, contacts were made with twelve companies that supply bidirectional inverters, where information was collected such as modes of operation; compatible battery technology; power and voltage; availability of sale in the Brazilian territory; types of applications (residential, commercial, and industrial); monitoring system; standardization and costs.

Among the twelve inverter suppliers contacted only four presented equipment with the power required for the pilot project and inverter integrated with the load controller and monitoring system. Between these suppliers, only two of them did not send their quotations containing the technical proposal offered, although one of them responded to the budget request justifying that their equipment is still in the development phase. During the supplier datasheet analysis, it was identified the existence of several advantages, such as the monitoring and control through the supervisory control system and data acquisition (SCADA) application, or other equipment with different application protocols. With all these factors looked at a national local manufacturer was selected and established, and a partnership aimed with the development of equipment meeting this R&D requirement. Thus, there is greater availability in terms of the bidirectional inverter development phases, plus a significant interaction between the supplier and the institution. Additionally, there is more interaction regarding the project phases, data access, communication protocol and updating the required functionalities.

Fig 2: UTFPR PV-battery-grid-tie-system (PV-system-left/bidirectional inverters-center/battery bank-right) [14].

The PV system rated power is 10.88 kWp, two bidirectional single-phase inverters with a rated power of 5 kW, and eighty lead-acid batteries 60 Ah each. The battery bank can store 57.60 kWh presenting a variable autonomy, and some parameters will be tested, to operate at times coinciding with peak hours. Some limits are set as the depth of discharge is at the lowest rate to extend its useful life according to the battery datasheet, since studies on aging of this type of technology, confirm that the maximum discharge depth can be up to 50% [15]. Furthermore, it is possible to extend its useful life, avoiding critical operating conditions, such as overload and deep discharge rates [16].

Figure 3 shows a simplified diagram connection of the inverter, PV panel, battery bank and their respective interconnections with the electric grid.

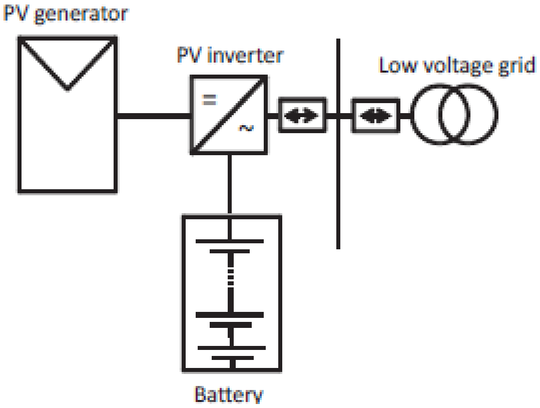


Fig 3: UTFPR simplified PV-battery-grid-tie-system diagram [17].

With the pilot project implementation, it is expected to analyse the most suitable modes of operations for use in UTFPR enabling the greater use of this energy. Thus, the intention is to increase the autonomy of commercial consumers, testing which are the best management strategies, providing the flexible operation between consumer and the electric grid.

3. Preliminary Results and Discussion

In order to develop the management energy strategies, we collected the energy demand data since 2018 through the electricity local company. With the daily demand data collection, we calculated the typical average profile which best represented the institution's demand and Figure 4 shows this curve. The month analysed for this work was May 2019, due to this period is previous of covid-19 pandemic, which represents more accurate demand profile.

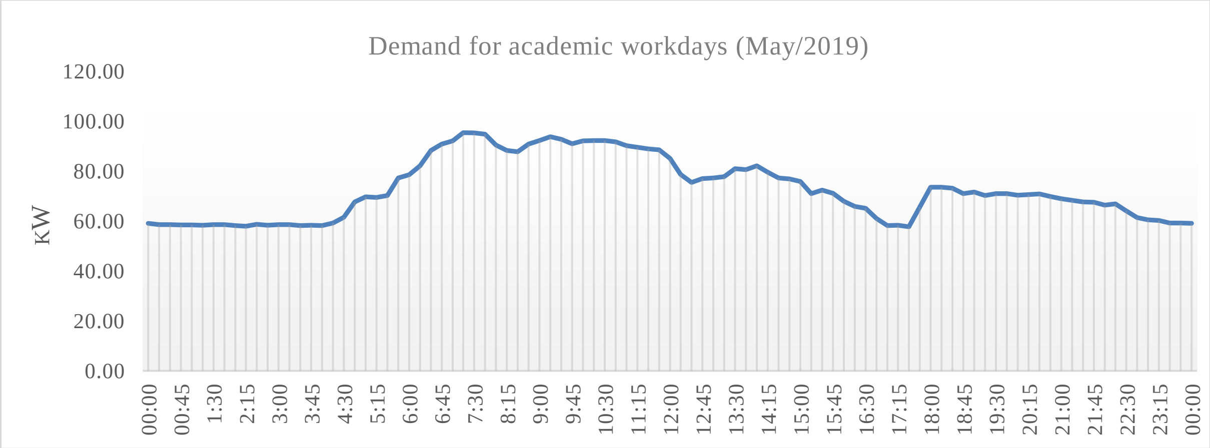


Fig 4: UTFPR building demand chart.

According to the Figure 4, we can identify the energy demand profile is during the day meeting the PV energy generation in this building. The PV-battery system is collecting input and output power data from the bidirectional inverters, and the initial battery bank discharge tests are being used for self-consumption purposes as shown in Figures 5a and 5b. The blue lines represent the direct current power (Pdc), which is the PV generation, whereas the red lines representing the battery bank operation charging and discharge power (power alternate current – Pac).

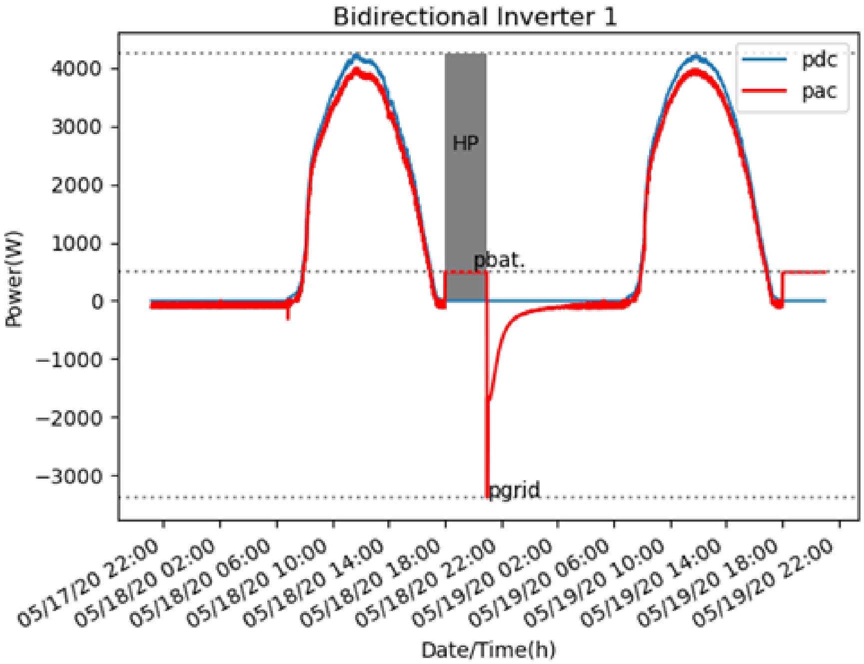


Fig 5: PV energy generation and battery bank charge-discharge operation

In Figure 5, a 48-hour cycle from May 18th to 19th, 2020, is shown, where the PV generation takes place (phase 1), and the peak generation is 4.24kWp (Inverter 1) happening between 7 am to 6 pm. The phase 2 occurs immediately in the peak hour at 6 pm (hours peak -HP starts at 6 pm till 9 pm) starting a scheduled discharge of the battery bank of 0.5kW. The last phase just happens after the end of schedule discharge operation, and immediately the electric grid charges the battery bank completing the daily cycling. Figure 6 shows more PV-Bat-system parameters related to PV power, battery voltage and current profile.

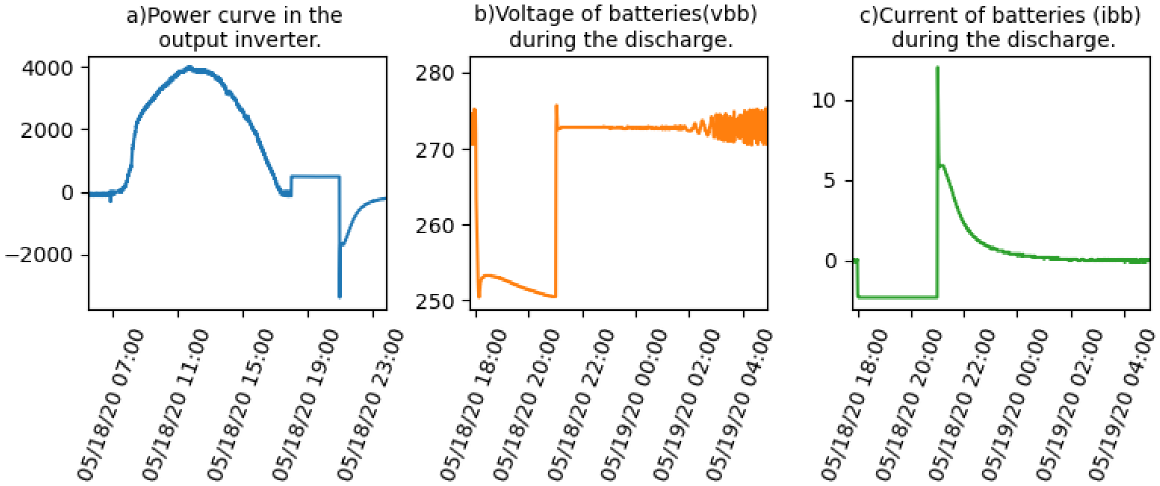


Fig 6: PV power curve collected through the inverter (b) Voltage of battery during the discharge (vbb) (c) Current of battery during the discharge (ibb).

The battery charging priority uses mains energy, after the end of the scheduled discharge the inverter disconnects the batteries, and in the next minute it starts charging with peak in the demanded power from the grid and in the current and battery voltage, after stabilizing. In Figure 6a) the power curve shows a negative peak of 3.38kW at the moment when the discharge ends and connects the storage system charger and in 6b) the variation of the battery voltage during the discharge and charge, 6c) the battery current during discharge is constant, the greater the current drained from the battery, the more it decreases its voltage, decreasing the remaining supply time power.

Figure 7 shows the combined data in one day-analysis comprising the building demand (bar gray), demand with PV generation (bar blue), demand with PV generation and battery bank discharge (bar 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).

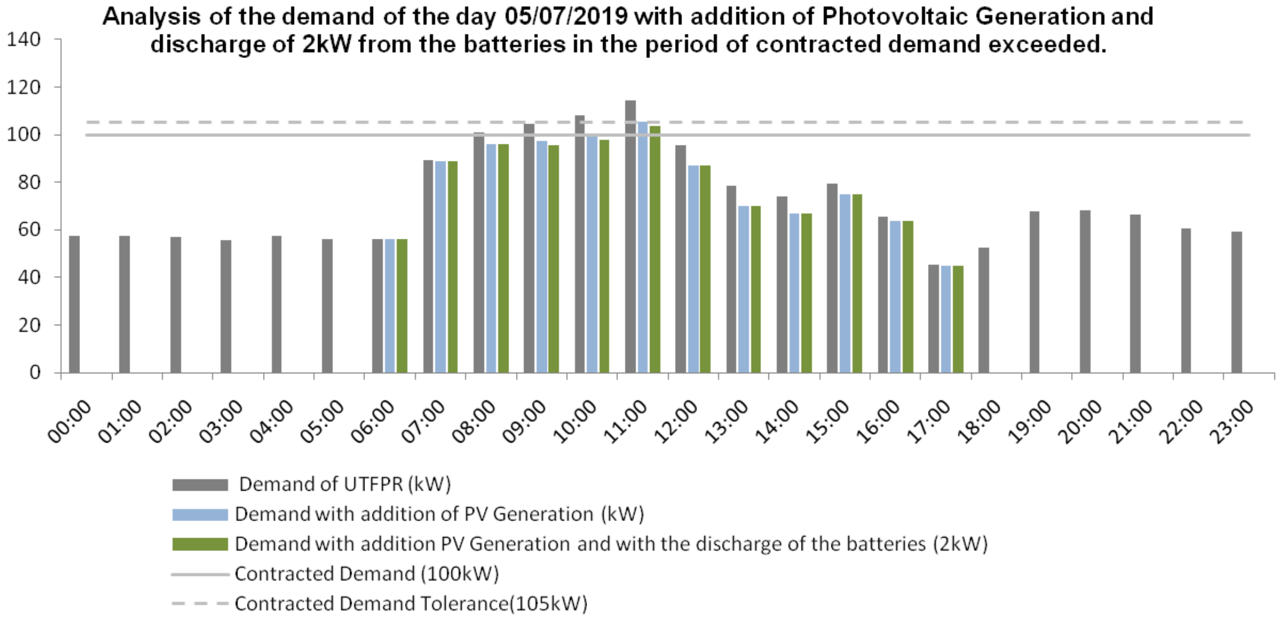


Fig 7: PV-battery-grid-tie system in one day analyse comprising the demand (bar gray), demand with PV generation (bar blue), and demand-PV-generation-battery bank discharge (bar green).

The calculation of the projected monthly and annual energy generation was performed applied the irradiation data in the tilted panel angle (25º) from the Atlas of Paraná Solar Energy database (Table 2) [18]. Having obtained the daily average monthly irradiation values in the PV tilted angle, it is estimated the average daily electricity generation through Eq. (1) [19].

Table 2: Irradiation data (kWh/m^2.day) [18].

Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
4.93	4.75	4.37	3.5	3.88	3.64	3.76	4.73	4.19	4.35	4.83	4.941

$$\mathrm{E} = \frac{Ppv\ x\ Htot\ x\ PR}{\mathrm{G}} \tag{1}$$

Where: E: average daily electricity (Wh / day); P_{FV}: peak photovoltaic power installed (Wp); H_{TOT}: monthly average daily solar irradiation for the locality in question (Wh / m^2.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 / m^2). Figure 7 shows the calculated results of the monthly and annual projected generation and the real PV-battery system generation in 2020.

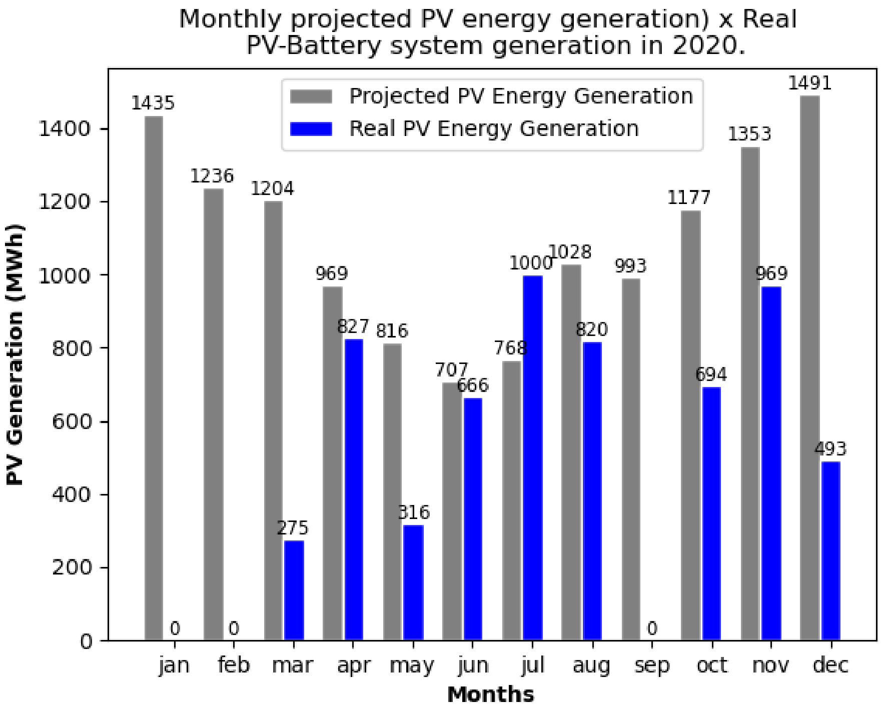


Fig 7: Monthly projected PV energy generation (kWh/month) and the real PV-Battery system generation in 2020.

As the battery energy storage process is based on battery state of charge (SOC) and depth of discharge (DOD), for the pilot project the appropriate rates for SOC and DOD will be defined, aiming at the safe operation of lead-acid batteries. Therefore, for each operating mode established for this system, the charge/discharge premise must be considered when operating the bidirectional inverter.

4. Conclusion

The expectation of the system's annual electricity generation is 13.2MWh, however the first year of operation the PV-grid-tie systems presented its generation of 6.09MWh, with a unit cost of US$0.13 per kWh, resulting in savings of US$ 781.17 and 589kWh discharged from batteries and the unit cost per kWh during peak hours is US$ 0.36 including taxes and savings of US$ 212.04 in 2020. These results can be explained due to the one of the bidirectional inverters was in the laboratory, where tests of communication with the equipment are being carried out, in addition, the routines of the energy management development. 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, avoiding 1.8 tonnes of CO_2 emissions.

With the implementation of this pilot project at the university, it is expected to demonstrate the feasibility of applying battery storage systems with PV generation, enabling the greater use of this energy. Thus, with the elaboration of the interaction scenario between generation, demand and charging of batteries, it is intended to increase the autonomy of commercial consumers, testing which are the best management strategies for the case analysed, with the flexible operation between consumer and power grid.

Therefore, through the pilot project, it will be possible to analyse the strategies and scenarios capable of meeting the needs of the location and making it possible to apply this unprecedented solution in the Brazilian scenario to consumers of all sizes. This development can enable a scenario with lesser uncertainties regarding the variables and standardization of PV-battery-grid-tie systems operation in the urban environments.

Acknowledgements

The authors would like to thank UTFPR for the support and infrastructure made available for the development of this research and COPEL-Distribution, for the support and funding through the grant “ANEEL PD2866-0464 / 2017 - Methodology for Analysis, Monitoring and Management of Distributed Generation by encouraged sources. The authors also thank Lactec for their financial support.

References

[1] F.R. Martins, E.B. Pereira, A.R. Gonçalves, R.S. Costa, F.J. Lima, R. Rüther, S.D.L. Abreu, G.M. Tiepolo, S.V. Pereira, and J.G.D. Souza, Atlas brasileiro de energia solar. 2nd ed. São José dos Campos, SP: INPE Press, 2017.

[2] National Electric Energy Agency (2021, Mar 8). Outorgas e Registros de Geração: Unidades Consumidoras com Geração Distribuída - Informações compiladas e mapa. [Online]. Available: https://app.powerbi.com/view?r=eyJrIjoiZjM4NjM0OWYtN2IwZS00YjViLTllMjItN2E5MzBkN2ZlMzVkIiwidCI6IjQwZDZmOWI4LWVjYTctNDZhMi05MmQ0LWVhNGU5YzAxNzBlMSIsImMiOjR9

[3] A. K. Shukla, K. Sudhakar, and P. Baredar, “A comprehensive review on design of building integrated photovoltaic system”, Energy and Buildings, vol. 128, pp. 99-110, 2016.

[4] S. Afxentis, M. Florides, C. Yianni, V. Efthymiou, I. Papageorgiou, G. Partasides, G. Papagiannis, G. Christoforidis, S. Mocci, A. Rubiu, and J. Oliveira, “Promotion of higher penetration of distributed PV through storage for all (StoRES)”. In *International Congress on Engineering and Sustainability in the XXI Century*, 2017, pp. 479-488.

[5] M. Gitizadeh, H. Fakharzadegan, “Battery capacity determination with respect to optimized energy dispatch schedule in grid-connected photovoltaic (PV) systems”. Energy, vol. 65, pp. 665-674, 2014.

[6] N. Opiyo, “Energy storage systems for PV-based communal grids”, Journal of Energy Storage, vol. 7, pp. 1-12, 2016.

[7] F. G. Üçtuğ and A. Azapagic, “Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries”, Science of the total environment, vol. 643, pp. 1579-1589, 2018.

[8] P. Balcombe, D. Rigby, and A. Azapagic, “Energy self-sufficiency, grid demand variability and consumer costs: Integrating solar PV, Stirling engine CHP and battery storage”, Applied Energy, vol. 155, pp. 393-408, 2015.

[9] X. Feng, H. B. Gooi, S. Chen, “Capacity fade-based energy management for lithium-ion batteries used in PV systems”. Electric Power Systems Research, vol. 129, pp. 150-159, 2015.

[10] P. Hanser, R. Lueken, W. Gorman, J. Mashal, and T.B. Group, “The practicality of distributed PV-battery systems to reduce household grid reliance”, Utilities Policy, no. 46, pp.22-32, 2017.

[11] S. A. S. Lopes, "Tecnologias de Armazenamento de Energia para Fornecimento de Serviços de Sistema." PhD dissertation, Dept. Elect. Eng. Universidade de Coimbra, Coimbra, Portugal.

[12] M. Y. Suberu, M. W. Mustafa, and N. Bashir, “Energy storage systems for renewable energy power sector integration and mitigation of intermittency”, Renewable and Sustainable Energy Reviews, vol. 35, pp. 499-514, 2014.

[13] A. A. Akhil, G. A. B. Huff, B. C. K. Currier, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, "DOE/EPRI electricity storage handbook in collaboration with NRECA" Sandia national laboratories, 2015.

[14] A. S. de Souza, J. D. A. Mariano, and J. U. Junior. "Sistema Fotovoltaico de 10kWp Conectado à Rede com Armazenamento de Energia em Curitiba." In *VII Congresso Brasileiro de Energia Solar-CBENS*, Fortaleza, Ceará, 2020.

[15] E. M. Krieger, J. Cannarella, and C. B. Arnold, “A comparison of lead-acid and lithium-based battery behavior and capacity fade in off-grid renewable charging applications”. Energy, vol. 60, pp. 492-500, 2013.

[16] S. Duryea, S. Islam, and W. Lawrance, “A battery management system for stand alone photovoltaic energy systems”. In: *Conference Record of the 1999 IEEE Industry Applications Conference*. Thirty-Forth IAS Annual Meeting (Cat. No. 99CH36370). IEEE, 1999. pp. 2649-2654.

[17] P. T. Moseley, and J. Garche, eds. Electrochemical energy storage for renewable sources and grid balancing. Newnes, 2014.

[18] G. M. Tiepolo, E. B. Pereira, J. Urbanetz Junior, S. V. Pereira, A. R. Goncalves, F. J. L. Lima, R. S. Costa, A. R. Alves, Atlas de Energia Solar do Estado do Paraná. Curitiba, PR: Itaipu Binacional Press, 2017.

[19] J. T. Pinho, M. A. Galdino, Grupo de Trabalho de Energia Solar (GTES). CEPEL - GTES. Manual de engenharia para sistemas fotovoltaicos. Rio de Janeiro, RJ: Cresesb - Centro de Referência para Energia Solar e Eólica Sérgio de Salvo Brito Press, 2014.