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Impacts of economic regulation on photovoltaic distributed generation with battery energy storage systems

Gabriel Nasser Doyle de Doile [a,b], Paulo Rotella Junior [c,d,e,*], Luiz Célio Souza Rocha [f], Karel Janda [e], Rogério Peruchi [c], Giancarlo Aquila [g], Pedro Paulo Balestrassi [g]

[a] Alternative and Renewable Energies Centre - Federal University of Paraíba, João Pessoa, Brazil
[b] Electric Engineer PhD Program, Federal University of Itajubá, Itajubá, Brazil
[c] Department of Production Engineering - Federal University of Paraíba, João Pessoa, Brazil
[d] Institute of Economic Studies, Faculty of Social Sciences, Charles University, Prague, Czech Republic
[e] Faculty of Finance and Accounting, Prague University of Economics and Business, Prague, Czech Republic
[f] Management Department - Federal Institute of Education, Science and Technology - North of Minas Gerais, Almenara, Brazil
[g] Institute of Production Engineering and Management, Federal University of Itajubá, Itajubá, Brazil

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ABSTRACT

Photovoltaic systems are largely involved in the process of decarbonization of the electricity production. Among the solutions of interest for deploying higher amounts of photovoltaic (PV) energy generation for reducing the electricity taken from the grid, the inclusion of local battery energy storage systems has been considered. Battery energy storage provides an energy buffer useful to better manage the fluctuations of PV energy production, or to serve the demand when the PV generation is absent or insufficient and the price of the electricity taken from the grid is high. While technically sound, the installation of a PV system with battery energy storage has to demonstrate its profitability in the specific context of application, also depending on the regulation in place in the relevant jurisdiction. This paper presents the stochastic economic feasibility analysis for the installation of distributed photovoltaic power plants facing the new Brazilian regulation of electric energy compensation system, and also considers the hourly tariff known as White Tariff. Three different sizes of distributed power plants are proposed, and the related models introduce battery banks to regulate the peak demand when tariffs are more expensive. In the absence of economic incentive policies to support this kind of renewable energy generation associated with battery energy storage systems, there is a lower probability of economic viability, especially for micro-plants up to 10 kW of installed power.

1. Introduction

The main component of the world energy matrix is from non-renewable sources [1]. Thus, the environmental impacts caused by burning fossil fuels are still growing worldwide [2] and the scientific community is researching sustainable and efficient energy solutions. Also an attention to this topic is increasing among worldwide policy makers [3]. Data on world electricity production [4] point out that renewable energies resources were the second largest contributor to global electricity production at the end of 2018. They accounted for 25.2 % of the world's electricity generation, mainly from hydroelectric, after coal with 38.2 % and ahead of natural gas, 23.1 %, and nuclear, 10.2 %.

According to the Generation Information System (SIGA) of Brazilian Electricity Regulatory Agency (ANEEL) [5], the Brazilian electric matrix is predominantly hydroelectric with 52 %, followed by thermoelectric, 26 %, wind, 14 %, and solar photovoltaic (PV), 9 %. Brazilian PV production essentially started when the Normative Resolution (NR) n^{o} 482 [6] was issued in 2012, which is the norm for distributed energy generation (DG). Meantime, the exponential growth is observed only from 2018 with the first PV plant auctioned by ANEEL in commercial operation.

Grid operations have been substantially altered due to the increasing use of intermittent sources of renewable energy (RES), both for DG and

* Corresponding author at: Cidade Universitária s/n, João Pessoa 58045-190, Brazil.
E-mail addresses: doyle13130@yahoo.com.br (G.N.D. de Doile), paulo.rotella@academico.ufpb.br (P. Rotella Junior), luiz.rocha@ifnmg.edu.br (L.C.S. Rocha), karel-Janda@seznam.cz (K. Janda), rsp@academico.ufpb.br (R. Peruchi), giancarlo.aquila@yahoo.com (G. Aquila), pedro@unifei.edu.br (P.P. Balestrassi).

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for utility-scale electricity generation [7,8]. These operational challenges can be minimized by the incorporation of Energy Storage Systems (ESS), which play a prominent role in increasing the reliability and stability of the grid [9], and performing functions of load displacement, operational support, and power quality [10]. ESS are categorized as [11,12]: electrochemical, electrical, mechanical, thermochemical, chemical, and thermal. Due to their versatility, electrochemical systems have been constantly used, especially batteries [12].

Battery energy storage systems (BESS) have been used more frequently in the provision of various services to the grid, at different voltage levels [13]. In DG applications, BESS are used to add flexibility to operational strategies, and allow the monitoring of objectives for the demand side management. In all situations, one aspect considered critical is the cost of the batteries [14].

The integration of distributed power plants with battery banks or other EES is a solution for the intermittence reaching better reliability in these generation systems [15]. Other authors [16,17] consider at least three PV generation challenges that can be solved by an appropriate ESS: (i) the dependence on the weather, (ii) the generation only during daytime, and (iii) the fluctuation of the generation. Battery banks are considered a more adequate ESS for small power plants due to its modularity and easy installation. However, even with battery prices decreasing in the last years [18], the battery bank cost is still an economic barrier.

There was no regulation for ESS in Brazil in force until mid-2023. Moreover, there are some studies related to the use of ESS in Brazil. Silva et al. [19] and Silva et al. [20] conducted technical-economic feasibility studies of PV systems with fuel-cell and BESS in an isolated community in the Brazilian Amazon region, using the Net Present Cost (NPC), Levelized Cost of Energy (LCOE) and initial cost of the system calculated by using the HOMER software. Nogueira et al. [21] proposed a model for the sizing and simulation of an isolated PV-wind system using BESS applied to a small rural property in southern Brazil. For that, Matlab was used to solve the optimization model whose answers of greatest interest were Loss of Power Supply Probability (LPSP) and NPC. Oliveira et al. [22] proposed a mixed integer linear programming model to optimize the dispatch of ESS connected to the grid in the Northeast region of Brazil, aiming at minimizing the operation and maintenance (O&M) costs. Dranka and Ferreira [23], performed a technical economic analysis of scenarios to increase the use of RES in the Brazilian electricity system future planning, using the EnergyPlan software. Campos et al. [24] analysed the natural complementarity of utility-scale wind and solar-PV sources with the use of ESS in the Brazilian Northeast region, focused on supply capacity, contingencies analysis and optimization. For this, the authors adopted the use of LPSP. Martinez-Bolanos [25] performed a feasibility analysis for replacing diesel generators, used to supply peak demand, for storage in BESS. For this, the authors analysed the feasibility of four different BESS technologies in a commercial establishment in the city of Campinas, Brazil, using the Homer software. Rocha et al. [26] proposed a multi-objective model for the insertion of ESS in utility scale hybrid plants.

Three other conceptual theoretical studies analysed the possibility of inserting the use of ESS in the Brazilian electrical system [27–29]. In particular, in Dranka and Ferreira [27], it was recognized that there is a limited deployment of ESS in Brazil because of its high hydropower capacity. In Silveira et al. [28] the applicability of different ESS technologies in Brazil was identified by considering the appropriateness of technical parameters such as power, energy, discharge time and response time with respect to the system requests, and BESS was considered appropriate to assist the integration of wind farms and solar power plants. And, Rocha et al. [29] proposed a theoretical model to assist in the creation of a regulatory framework aimed at inserting the ESS into the Brazilian electricity system.

Specifically, in the economic feasibility context, few studies that analyse the Brazilian scenario were found. Silva and Branco [30] in their study for a Northern Brazilian city concluded for unfeasibility of small PV power plant with battery banks as ESS. For this, the authors conducted a deterministic study using the System Advisor Model (SAM) developed by the National Laboratory of Renewable Energy (NREL) to analyse the economic viability through responses such as Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Payback. In a more recent study [31] the authors, also, concluded for economic unfeasibility of hybrid solar PV plus lithium-ion battery banks. The authors proposed a linear optimization model for monitoring the daily energy operation, in addition to analysing the deterministic economic feasibility using tools such as NPV, Internal Rate of Return (IRR) and Payback.

On the other hand, Cucchiella et al. [32] conducted a deterministic analysis of different scenarios for photovoltaic energy systems with battery storage for residential areas, without subsidies, in Italy. Through the NPV criteria, they conclude that residential PV plants with battery banks are a profitable business in a fully developed electricity market, like in Italy. However, they recommend economic incentives at least in the beginning of market development for countries with electricity trade system not mature yet. More recently, in a systematic literature review, Rotella Junior et al. [13] showed that few studies have carried out the economic and financial feasibility of using BESS. Most of the studies identified by the authors concentrate efforts on optimization models that adopt a cost parameter. Still, in the world scenario, studies that use the Monte Carlo Simulation (MCS) method applied to financial responses, such as NPV, IRR or LCOE, are rare.

Thus, the present study aims to assess the economic feasibility of distributed PV power-plants with battery banks as ESS. The main barriers for ESS in Brazil are the lack of techno-economic regulation and incentives, as feed-in-tariffs or economic subsidies. Stochastic analyses are carried out by varying seven of the main variables in three sizes of PV power plant: micro plant, up to 10 kW; mini plant, from 10 kW up to 1 MW, and small power plant from 1 up to 5 MW installed power. In all of them, battery banks supply capacity for five hours, one day, or four days.

Therefore, the novelty of this study is to analyse, in a stochastic way, the economic viability of photovoltaic DG with battery banks as ESS, given the recent regulatory adjustments implemented in Brazil in 2023 with Law number 14,300. To the best of our knowledge, this analysis has not been performed before. Also, its contributions go beyond the analysed case, as the political implications presented bring important information to stakeholders in the electrical systems of other countries (especially those with similar economic regulation), including public policy makers.

In addition to this introductory section, Section 2 presents the context and theoretical considerations. Section 3 presents the data collection, input and output variables, and research method used. In Section 4, the results are shown with their discussion. Finally, the conclusions are summarized in Section 5.

2. Theoretical background

2.1. Regulation in force

The NR n° 482 establishes grid access conditions for DG, creating the figure of prosumer, the consumer with DG installed that is allowed to inject the energy surplus into the distribution grid. This normative also establishes standards for the net metering system that, in Brazil, is called Electric Energy Compensation System (EECS). In its first presentation, the EECS provided that each kilowatt-hour injected into the grid should be offset by the same value, i.e. the prosumer that inject 1 kWh into the grid is allowed to consume 1 kWh from the grid later without any payment. The new regulation, to be in-force, says that only the energy production cost, corresponding to 43 % of the tariff, should be compensated and the other costs that compose the energy bill shared among all consumers. It means the end of cross-subsidy, where consumers with no DG pay for grid cost and sectoral charges, alone [33]. This end of the cross subsidy causes a significant reduction in the economic feasibility of distributed photovoltaic micro-plants [34]. In this perspective, ESS applied to DG can become attractive [35], as energy would no longer be injected into the grid and would be available for later consumption, without the discount proposed in the new regulation.

The regulation changes proposed by ANEEL were planned to be finished in 2020, but their application was postponed and, then in January of 2022, the National Congress passed the Ordinary Law number 14,300 [36] where a transition period until 2030 was established. In such period, the amount of compensation (net metering) will be reduced year by year. By 2030 ANEEL should issue a new regulation to be in force from that year. The last change of NR 482 was related to the EECS, where only 43 % of the energy injected into the grid will be compensated. This amount corresponds to the production cost of electric energy and, will be the most probable ANEEL regulation from 2030 as stated by Costa et al. [37]. In this study the effects of ANEEL proposed regulation are considered in force to show the necessary adjustments in regulation in order to maintain DG economic viable in Brazil.

In this article, beyond the EECS, a net metering system where only a part of energy injected into the grid is late compensated by consumption from the grid, the following regulatory concepts are considered: i) Availability cost, a minimum fee charged to all consumer; ii) White Tariff (WT), which consists of hourly billing, with three tariff points (intermediate, off-peak and peak), as shown in Fig. 1; iii) Tax incentives, some government tax exemptions for prosumers.

Fig. 2 shows the electricity production and consumption schemes. In some scenarios, production is not sufficient to meet the demand at one or more tariff points. In these cases, a demand from the grid, in addition to produced energy, is necessary to supply all consumption, columns (*i*) and (*ii*). Column (*iii*) shows the consumption division between own demand and remote third-part demand, where the sum must be equal to all consumption. For better economic comparison, it is considered that all the surplus energy, that energy injected into the grid, is used for own consumption by own demand added to the remote consumption of third parties, columns (*iv*) and (*v*). For more information, see Doile et al. [39].

2.2. Economic decision criteria

NPV is an important financial tool that can be calculated by a cash flow considering several inputs, such as initial investments, management costs, life of facilities, operating time, minimum attractiveness rate, electricity tariffs, taxes and, eventually, credits from state programs or subsidies, among others [40]. Since that Li et al. [41] have claimed that *NPV* is the most adequate method for economic analyses among others, many other papers were published using this financial tool. NPV is still the most used assessment economic tool, as shown in recent studies [42,43]. The *NPV*'s goal is to calculate the current value of future sum of income and expenses, discounted by a desirable discount rate, the Minimum Attractiveness Return Rate (*MARR*). *NPV* is calculated by the Eq. (1) [44]:

$$NPV = -C_0 + \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} = -C_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \ldots + \frac{CF_n}{(1+r)^n} \tag{1}$$

where C_0 is the initial investment; CF_1 to CF_n are the annual cash flows (incomes and expenses) for the project; n is the period (year) and r is the *MARR*.

An economic assessment supports the decision for a given investment [45]. Several inputs are commonly used to find, through the cash flow, besides the *NPV*, two other output variables: the Internal Rate of Return (*IRR*) and the Discounted Payback (*DPB*).

The discount rate that zeroes the *NPV* is the so-called *IRR*, which is an indicator to be compared to a discount rate desired by the investor [46]. A higher *IRR* than *MARR* means that the project is viable, with a positive *NPV*. Lower *IRR* than *MARR* results in a negative *NPV* indicating the project's unfeasibility. The *IRR* could be calculated by Eq. (2):

$$\sum_{i=1}^{n} \frac{CF_i}{(1+IRR)^i} = C_0 \tag{2}$$

DPB is another economic indicator widely used in economic analysis of projects [47]. It is the time that the project needs to return to the investor all the investment made. In other words, it is the moment when the investment on the project begins to make a profit. The shorter the *DPB* is, the more attractive the project will be. To obtain the *DPB*, the sum of incomes and expenses is brought to the initial period and compared with the initial investment. Thus, the *DPB* will be the time in which the sum of cash flows in the initial year is equal to initial investment. In Eq. (2), when fixing the *IRR* equal to the *MARR*, the *DPB* will be given by the n (year plus fraction) in which the equality becomes true.

Through the MCS, uncertainties related to the estimation of the *NPV* can be incorporated into economic feasibility studies. The MCS is performed through numerous iterations, in which the uncertainty of the parameters is entered from the selection of different random values [48,49].

In this case, a probabilistic model is built, where parameters can assume a range of possible stochastic values. The parameters will be represented by probability density functions (PDF) based on real parameters. Arnold and Yildiz [50] shown in their study that the probability density function determination for the entries of the model is the main step in the MCS. For example, the PDF function for the NPV is presented according to Eq. (3):

$$P_{NPV>0}(x_1, \ldots, x_n) = \int_0^{+\infty} pdf(NPV)\, dNPV \tag{3}$$

where P_{NPV} is the accumulated probability of *NPV*s; $\{x_1, \ldots, x_n\}$ *represent* the random variables; and *pdf*(*NPV*) represents the PDF of *NPV* in the studied project (*NPV*).

3. Materials and methods

3.1. Input variables

For this study seven inputs were necessary: i) the nominal power (P_n), also called installed capacity, in kW; ii) solar irradiation, in kWh/

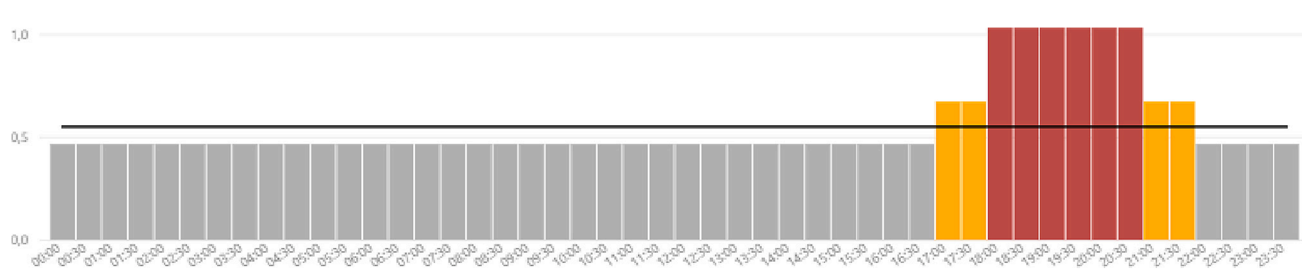

Fig. 1. White Tariffs average graphic. Source: NR 414 [38].
Notes: peak tariff in red, intermediate tariff in yellow, and off-peak tariff in grey. Black line set the conventional tariff. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

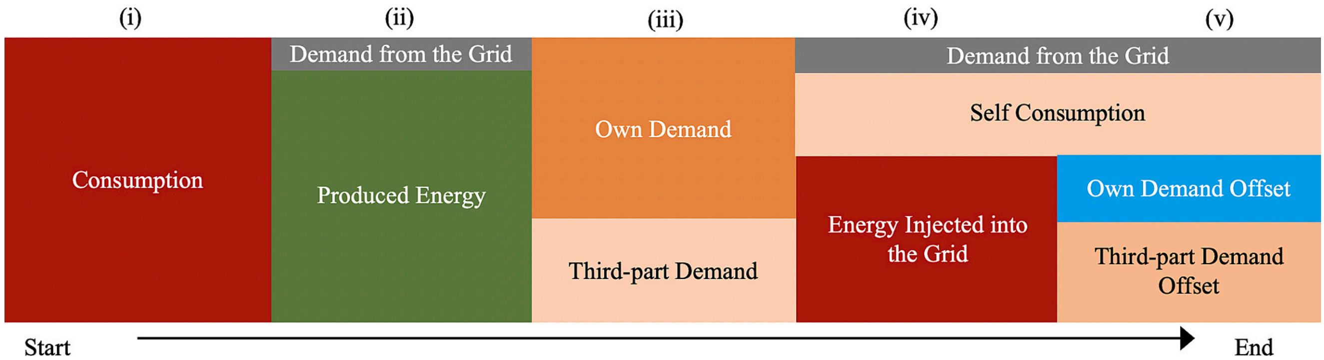

Fig. 2. Electricity production and consumption scheme.

m^2 per day; iii) consumer demand, in kWh per month; iv) electricity tariff, in USD/kWh; v) initial investment of PV panels array, in USD/kW; vi) initial investment of battery bank, in USD/kWh; and, vii) the Minimum Attractiveness Return Rate (*MARR*), in percent.

3.1.1. Proposal for power plants classification

The NR 482 divides into two classes, microgeneration up to 75 kW and mini generation from 75 kW to 5 MW. However, considering the GD concessions in-force until July 2020 [5], installations classified as microgeneration have P_n of 1.16 kW in average. Those classified as mini generation have an average P_n of 1.5 MW. Of the 3751 installations classified as micro plant, only 24 of them, or 0.65 %, have a $P_n > 10$ kW. Among the mini plants, 61 % have $P_n < 1$ MW. Therefore, based on above data, the classification of DG power plants provided by NR 482 is inadequate to Brazilian reality and will be compared to other countries regulations to propose changes.

In the USA, according to Fu et al. [51], there are three DG classifications: Residential, from 3 to 10 kW of installed power; Commercial, from 10 kW to 2 MW and Utility-scale above 2 MW. In the UK, as regulated by OFGEM [52], to be eligible for feed-in tariff scheme, installations must follow the classification: <4 kW; from 4 up to 10 kW; from 10 up to 50 kW, and from 50 kW up to 5 MW. In Ireland [53], also there are three DG classifications, and the maximum installed power is only 50 kW. In Italy, the classes of nominal power are from 1 to 3 kW; over 3 kW up to 20 kW; over 20 kW up to 200 kW; over 200 kW up to 1 MW; over 1 MW up to 5 MW, and over 5 MW [54].

The study presented in this paper adopts a proposed classification into three ranges of installed nominal power P_n, as follows:

a) Micro plant, with P_n up to 10 kW. Predominant in residential installations on the roofs or walls, with micro frequency inverters.
b) Mini plant, with $P_n > 10$ kW up to 1 MW. Predominant in commercial installations or small industries. These can use microinverters or centralized frequency inverters, according to installed P_n.
c) Small power plant, $P_n > 1$ MW up to 5 MW. These are facilities whose main objective, in general, is to share energy with remote consumers. For economy of scale reasons, they will use centralized frequency inverters and connection to the three-phase electrical grid.

3.1.2. Initial Investment and costs

Firstly, the power plant and battery bank adequate sizes have to be determined. For this purpose, the demand is used as a main input factor, together with the solar irradiation and standard panel data. The standard panel data, defined by Doile et al. [55], are 250 W of nominal power, 1.6 m^2 of useful area, and 19 % efficiency. As demand and solar irradiation are stochastic input variables, the panel and battery bank layout sizes will be calculated in each MCS iteration. P_n in kilowatts is calculated by Eq. (4).

$$P_n = 0.156 \times \frac{D_m}{R_m \times \varepsilon} \tag{4}$$

where 0.156 is the nominal power of a standard panel in kW/m^2; D_m is the average demand in kWh; R_m is the average solar irradiation in kWh/m^2, both in the same time dimension, and ε is the dimensionless standard panel efficiency. In this paper 30-year useful life project and 0.7 % annual efficiency loss of the PV panels [56] are considered. The inverters' useful life is 15 years and the lead-acid batteries are substituted each five years.

The battery bank size will be determined by the total energy consumption in 5 h peak demand, the total energy consumption in a day, and the total energy consumption in four days. In the first case the battery bank must be able to supply the demand during the peak hours to avoid the higher tariffs. In the other cases, the battery bank is called to supply the demand in case of lack of production or energy outage in a period from one up to four days. Battery bank nominal power for 5 h, one day, and four-day supply in kilowatts will be calculated by Eqs. (5) to (7), respectively.

$$B_{P5} = \frac{D_{pk}}{5} \tag{5}$$

$$B_{P1d} = \frac{D_{pk}}{5} + \frac{D_{19h}}{19} \tag{6}$$

$$B_{P4d} = \frac{D_{pk}}{5} + \frac{D_{19h}}{19} + \frac{D_{72h}}{72} \tag{7}$$

where, B_{P5}, B_{P1d}, *and* B_{P4d} are battery bank nominal power in kW, by respective supply time capacity; D_{pk} is the total demand in 5 h daily peak in kWh, D_{19h} is the daily off-peak demand, and D_{72h} is the three days ahead demand, both in kWh.

In this study, battery banks vary from 40 % up to 100 % for 5 h autonomy; from 60 % up to two times the installed power for one day autonomy; and from one up to three times *Pn* for four-days autonomy. The maximum battery discharge of 80 % was considered, as predicted by Glaize and Genies [57].

Battery modelling is crucial in a hybrid power system study [58] due to the lifetime uncertainty since the cost of battery banks is a significant investment parcel. Typically, the battery's life cycle is measured by the loss of its energy supply capacity compared to its initial capacity. <80 % capacity is considered a dead battery [18]. On the other hand, in recent studies [59,60] five-year lifetime lead-acid batteries are considered. So, this paper considers a five-year lifetime with 4 % efficiency loss per year for lead-acid batteries.

In this article, a price survey has defined the PV panels and inverters' average prices as also carried out in other literature studies [34,55]. Similar survey was done here to determine the battery banks average price and the density function shape to be used in stochastic simulations. Lithium-ion battery prices have been found to be 30 times higher than lead-acid battery prices, in average on Brazilian retail market. Even though the lifetime of the lithium-ion battery is twice the lifetime of the lead-acid battery [17,61], the NPV of initial investments plus re-investments is still less for lead-acid batteries in Brazil. An 80 % reinvestment in battery banks was considered each five years.

Battery bank size will be chosen by consumer profile. It is expected that all consumers will store enough energy to avoid grid consumption on the peak time, where tariffs are high. However, as the energy surplus injected on the grid is only 43 % offset and grid consumption is tax charged when the consumers do not have energy credits, some of them will chose to store energy for a time greater than the peak time. Based on Brazilian electricity outages history [62], let us suppose 20 % are extremely conservative and choose four-days storage systems, 50 % choose one-day storage systems capacity, and 30 % choose five-hour storage systems.

3.1.3. Solar irradiation

Brazil has an excellent annual average of daily total of global solar irradiation, as shown by Pereira et al. [63] in their atlas. That atlas is based on several studies make by Brazilian universities coordinated by the Modelling and Studies on Renewable Energy Resources Laboratory (LABREN), in Earth System Science Centre (CCST) of the National Institute for Space Research (INPE), a governmental body to make spatial phenom research.

Also, The Power Project, managed by Langley Research Centre (LARC) of the National Aeronautics and Space Administrations [64] was an important data source for this paper. Combining these two data sources, the density function shape used in this study varies from 2.4 up to 7 kWh/m^2 per day, following a beta-shaped distribution curve.

3.1.4. Other inputs

This study considers the electricity demand and electricity tariffs from ANEEL's database [65] [66]. According to EPE [67], in the last five years, residential demand grew by an average of 2.21 % per year, commercial demand 0.36 % per year and industrial demand decreased by 0.24 % per year. These percentiles are adopted in this work, except for industrial demand, which remained constant. The tariffs real growth adopted here, beyond the inflation measured by IPCA, an official Brazilian indicator, was 0.63 % based on historical data [68]. Such historical data allowed to define the data range and its form of distribution.

The *MARR* is an important input parameter varying with the project risk, liquidity, and cost of opportunity [69,70]. In general, EPE [71] uses 8 % as *MARR* for medium- and long-term planning studies. This value was defined here as the central point of a normal distribution with 0.5 % standard deviation.

3.2. Parameters setting for economic simulation

In this study, as informed, three base cases were used considering proposed power plants classification. Firstly, a deterministic analysis using the input parameters average was carried out to validate the simulation datasheet.

The MCS tool is a very versatile tool that allows, among other things, to add constraints and correlations on stochastic variables. For example, it was used a constraint on solar radiation, which is present only during daytime. However, correlation between input variables was not used. This choice is based on findings from Doile et al. [55], who studied the economic feasibility of solar PV among Brazilian geographic regions. These authors attested that the correlation among solar radiation and

Table 1
Definition of parameters for the input variables.

Parameter	Distributions	Case	Minimum	[a]More probable	Maximum
Nominal Power [kW]	Triangular distribution	Micro	0.5	1.45	10
		Mini	10	109	1000
		Small	1000	1400	5000
			Location	Scale	Form
Power plant Investment [USD/kW]	Weibull distribution	Micro	650	700	2
		Mini	500	550	2
		Small	500	550	2
			Location	Scale	Form
Battery bank Investment [USD/kW]	Weibull distribution	Micro	268	130	2
		Mini	275	140	2
		Small	290	145	2
				Average	Scale
Energy Tariff [USD/kWh]	Logistic distribution	Peak tariff		0.2078	0.0272
		Intermediate		0.1374	0.0166
		Out of peak		0.0849	0.0073
		Conventional		0.1075	0.0095
			Minimum	Beta parameter	Maximum
Solar radiation [kWh/m^2]	Beta distribution	All cases	2.40	1.51	7.00
			Location	Scale	Form
Electrical Demand [kWh]	Gamma distribution	Micro	92	250	1,9
		Mini	1840	25,000	1,9
		Small	184,000	100,000	1,9
			Average	Standard deviation	
MARR [%]	Normal distribution	All cases	8 %	0.5 %	
			5 h	1 day	4 days
Battery bank size [kWh]	Discrete distribution	All cases	30 %	50 %	20 %

[a] Average power calculated from ANEEL data [33].

other variables, is not relevant for economic results, that are strongly affected by electricity tariffs and demand. Moreover, as presented in the study by Poblete-Cazenave and Pachauri [72], also in Brazil, demand is more affected by people's social-economic conditions than natural conditions, as weather.

To perform the stochastic analyses, the MCS was performed using the Crystal Ball® software and the parameters varied as shown in Table 1. 10,000 simulations were generated, as adopted in the literature [73,74], that proved to be sufficient for convergence of results.

The nominal power follows a triangular distribution between classification limits power of the plant. The most probable nominal power, shown in Fig. 3, was calculated by the average of ANEEL data [33] for micro and small plants and approximated to mini plant, a new classification proposed in this paper. Weibull distribution was the best approach for investment variation, based on price survey data. This curve shape is one where the scale means the main value more present in the sample. Small values follow a fast-decreasing curve and high values, a smooth decreasing curve determined by form parameter. The location parameter is a positive displacement of the shape on the x-axis. Energy tariffs follow a logistic curve that is like a normal curve but decreasing more quickly. Solar radiation data are represented with a Beta distribution (able to represent non-zero values only in the specified range from the sunrise to the sunset), while electricity demand is represented by a Gamma distribution. Finally, the *MARR* follows a normal curve with 8 % average and 0.5 % standard deviation. Battery size is a discrete function based on consumer behaviour.

In this work, the regulation changes are considered to be approved and in force, including the EECS, the WT, and the proposed plant sizing. Thus, based on ANEEL data [33], annual average of generation and demand are shown in Table 2.

To set up a practically significant approach, it is considered a mix among residential, commercial and industrial demands for each classification of plant, as shown in Table 3. Micro plants are predominately to supply residences but also small commerce. Mini plants are more adequate for commercial buildings and small plants for medium size industries.

Then, in a simplified way, the overall process flow is described in Fig. 4.

4. Results and discussion

The performance of three DG unit sizes including remote consumption and the WT was compared. In the first simulations, whose result is shown in Table 4, the probability values of obtaining an $NPV \geq 0$, an $IRR \geq 12$ % and, a $DPB \leq 5$ years, without Energy Storage System – ESS, was analysed. The selection of these points of comparison makes it possible to assess the feasibility against different investor profiles. When taking the NPV as the main economic criterion, the values are always compared with the MARR, that is, it is decided on its feasibility ($NPV \geq 0$). When the requirement of an $IRR \geq 12$ % is adopted, a more conservative profile is met. Another point is taken when considering a $DPB \leq 5$ years, which can be seen as the requirement for an even more rigorous profile. Therefore, the results were presented in three distinct profiles, which are not self-excluded and are part of the same financial analysis.

By first results, economic indicators are better for Conventional Tariff (CT) than WT for mini and small plants. However, the opposite happens for microgeneration plants. It happens due to the out-off peak PV production in conjunction of the rule, where energy surplus is

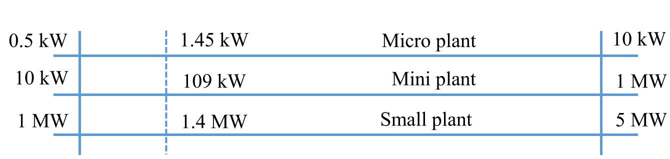

Fig. 3. Nominal power limits for each plant classification.

Table 2
Electrical production and demand by tariffs points.

Tariff point	PV production	Demand		
		Residential	Commercial	Industrial
Off-peak	97.96 %	65.35 %	67.70 %	92.54 %
Intermediate	1.70 %	11.47 %	12.85 %	5.74 %
Peak	0.34 %	23.18 %	19.45 %	1.72 %

Source: Based on [5].

Table 3
Demand mix among power-plant classification.

Classification	Demand		
	Residential	Commercial	Industrial
Micro plant	90 %	10 %	0 %
Mini plant	10 %	50 %	40 %
Small plant	0 %	40 %	60 %

preferentially offset at the same tariff point that was produced. The industrial demand at peak period is very small when compared to the demand at out-off peak. This fact, coupled with the CT that is higher than WT in the off-peak period leads to a better economic performance of these projects, even against the common sense.

The stochastic results varying all inputs, as explained in Table 1, with the addition of battery banks and after 10,000 simulations with MCS, are shown in Table 5. Once again, the probability of economic viability for the three power-plant classification proposed in this study is presented using the WT scheme. The results show a low probability of economic viability in some scenarios with battery banks. The *NPV* for most five-hour battery bank scenarios shows profitable projects. However, the *IRR* shows low probabilities of results >12 % per year and, in very few scenarios the entrepreneur will have return in periods up to five years.

For a better understanding of the results, Figs. 5 to 7 are presented. In these, the histogram represented in Dot Plot and cumulative distribution function (CFD) resulting from the simulations are presented. For example, for the micro plant with 5 h battery bank capacity, the cumulative probability for $NPV < 0$ is 37.97 % and therefore P ($NPV \geq 0$) = 62.03 %.

Next, the Bubble Plot is presented, in which the size of the project is represented by the size of the bubble illustrated in Fig. 8. The analysis of this figure provides some interesting information. Firstly, it is observed that smaller projects (micro plants) are those that, in general, have a lower average NPV. In addition, projects with 4-days battery bank capacity had a low probability of viability, resulting in lower average NPV values for all plant sizes. Finally, as a result of the scale gain of the generation project, the larger the plant size, the higher the average NPV for 5-h and 1-day battery banks capacity.

Fig. 9 shows the Multi-vari chart, which is a graphical representation of the relationships between factors (plant classification and battery bank capacity) and a response (NPV). The results in the figure reinforce the issue of scale gain for DG projects that use 5 h and 1-day battery banks capacity. However, the behaviour changes when considering 4-days battery bank capacity. The explanation for this fact is that, in larger projects, a greater amount of energy is produced, and the sizing for a battery bank with autonomy for four days, results in a very high investment value, harming the economic viability of the DG project.

If there were economic viability for battery banks, all consumers would desire at least five hours battery bank capacity, to avoid grid consumption during the peak point, where tariffs are highest. Based on Brazilian electricity outages history, 50 % of consumers in average would choose one-day battery bank capacity. Considering that Brazil has some regions with high annual precipitation, 20 % of consumers would choose four-days battery bank capacity. Table 6 shows the results for these consumers behaviour, that is still economically unfeasible in

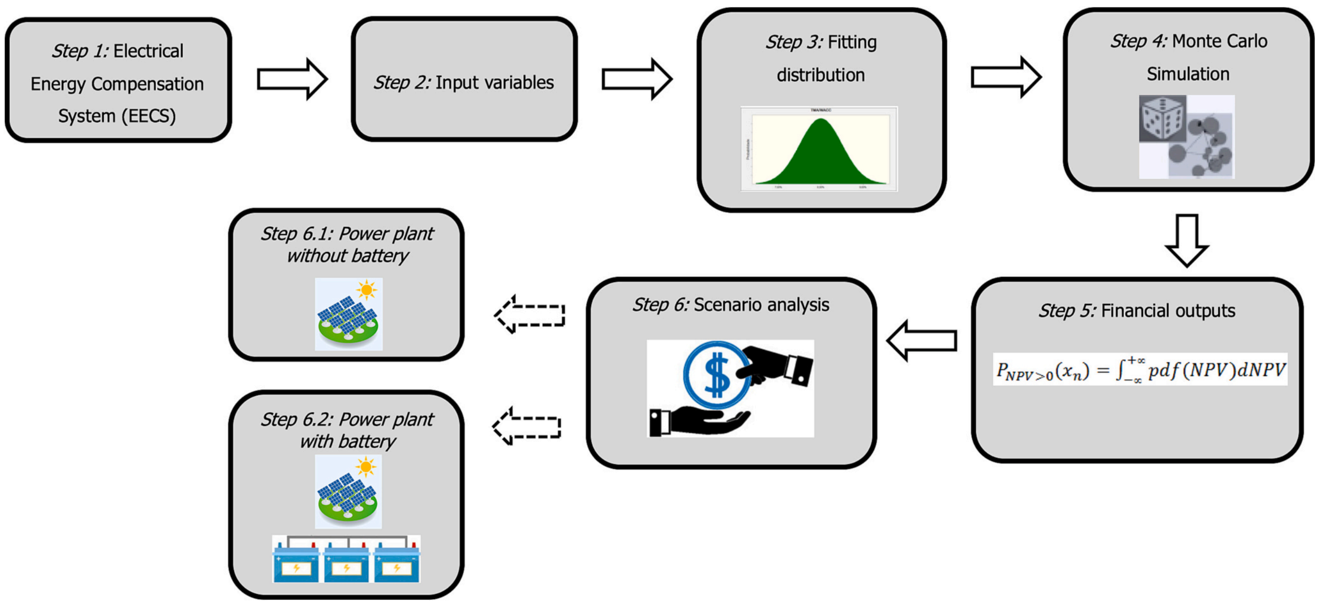

Fig. 4. Research flowchart.

Table 4
Probability of economic viability by power plant classification using CT and WT without battery banks.

Output classification	White Tariff			Conventional Tariff			Difference WT-CT		
	NPV[a]	*IRR*[b]	*DPB*[c]	*NPV*[a]	*IRR*[b]	*DPB*[c]	*NPV*[a]	*IRR*[b]	*DPB*[c]
Micro plant	81.49 %	53.89 %	8.11 %	79.26 %	51.81 %	7.91 %	2.23 %	2.08 %	0.20 %
Mini plant	94.42 %	80.21 %	20.13 %	94.08 %	81.39 %	24.28 %	0.34 %	−1.18 %	−4.15 %
Small plant	95.32 %	81.23 %	18.78 %	96.82 %	86.52 %	26.51 %	−1.50 %	−5.29 %	−7.73 %

[a] $P\ (NPV \geq 0)$.
[b] $P\ (IRR \geq 12\ \%)$.
[c] $P\ (DPB \leq 5$ years).

Table 5
Probability of economic viability by power plant classification with ESS and WT.

Output Classification	5 h battery bank capacity			1-day battery bank capacity			4-days battery bank capacity		
	NPV[a]	*IRR*[b]	*DPB*[c]	*NPV*[a]	*IRR*[b]	*DPB*[c]	*NPV*[a]	*IRR*[b]	*DPB*[c]
Micro plant	62.03 %	35.47 %	1.37 %	53.28 %	26.45 %	0.69 %	33.37 %	12.23 %	0.09 %
Mini plant	75.55 %	49.27 %	3.81 %	64.32 %	37.67 %	1.73 %	39.43 %	16.16 %	0.18 %
Small plant	81.25 %	56.29 %	4.43 %	68.88 %	40.94 %	1.67 %	43.35 %	17.30 %	0.16 %

[a] $P\ (NPV \geq 0)$.
[b] $P\ (IRR \geq 12\ \%)$.
[c] $P\ (DPB \leq 5$ years).

almost all scenarios. In addition, the results for the same scenarios using CT are shown. The worst result is for micro plant, that one predominantly for residential users. Also, the *NPV* shows that projects can be economically feasible in some five-hours and one-day battery bank capacity scenarios, however, the vast majority with long-term investment return. Micro plants with five-hours and one-day battery bank capacity can be economically viable, in few scenarios. The same happens with mini and small plants in other battery bank capacity scenarios. Even with the results for all scenarios, shown on Figs. 5 to 7, a case study with specific simulations is recommended, if the investor accepts a return rate <12 % annually and a financial return within more than five years.

Comparing WT with CT, it is evident that WT is better for micro plants, as well as it is worst for mini and small plants. It must be emphasized that this phenomenon happens due to the compensation scheme (EECS), where the injected energy must be compensated as a priority at the same tariff point in which it was generated. The most generated energy by solar PV is in the out-off peak tariff point.

There are some similar economic feasibility studies for distributed photovoltaic generation with and without energy storage systems in Brazil since the beginning of the 2010s. Table 7 shows a comparison between the previous studies and the present study. The studies were carried out in different years, therefore different prices and tariffs were considered. As it can be seen, panels price dropped while tariffs grown. These facts, by themselves, are enough to make distributed generation from PV economic feasible (as seen in Table 4). However, when added battery banks as storage systems, the set had a low probability of economic feasibility for battery banks with greater capacity (as seen in Table 5).

As the PV business was beginning in Brazil, Holdermann et al. [75] used UK prices to calculate investments. In that time electricity tariffs were slightly subsidized by reduction in energy prices, contributing for business unfeasibility, results obtained using the PV*Sol software. Rocha et al. [45] studied the effects of tax exemption. For that, the authors used the MCS to generate simulations in which the output was the *NPV*. With

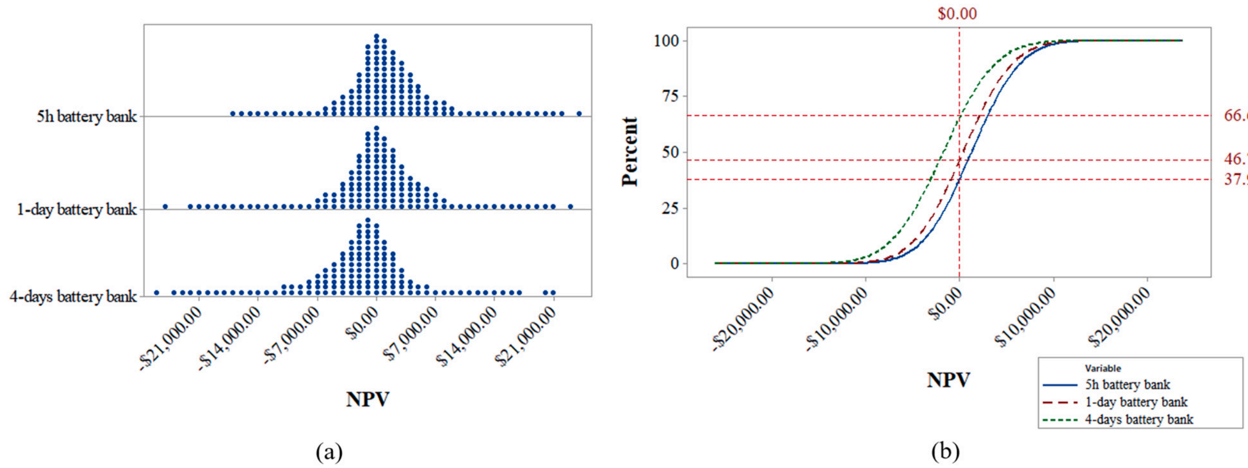

Fig. 5. Micro plant (a) Dot plot of NPV and (b) Cumulative probability of $NPV < 0$.

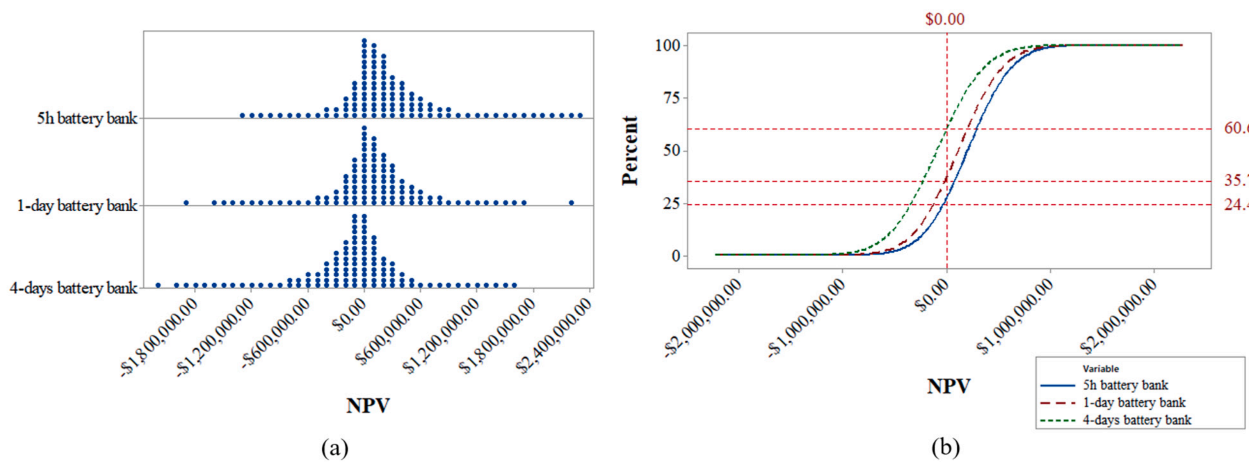

Fig. 6. Mini plant (a) Dot plot of NPV and (b) Cumulative probability of $NPV < 0$.

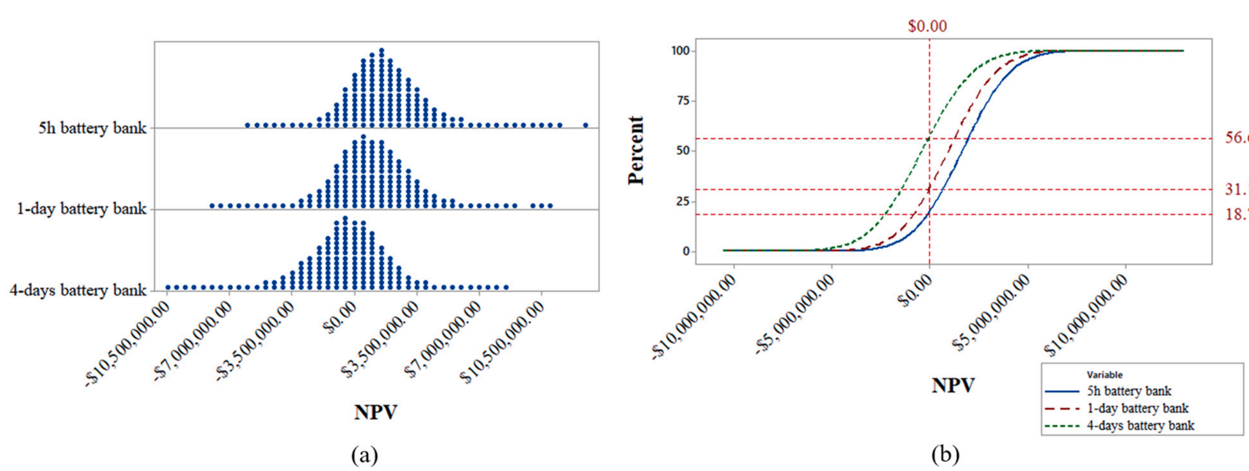

Fig. 7. Small plant (a) Dot plot of NPV and (b) Cumulative probability of $NPV < 0$.

no tax, the PV enterprise started becoming feasible from that time. Silva and Branco [30] is the first study to consider battery storage system combined with PV distributed generation. The battery prices turned the projects unfeasible. Two years after Deotti et al. [31] repeated the study with currented data and have had the same conclusion of unviability. More recently, Doile et al. [55] with no energy storage systems, using the current lower prices and high tariffs, the PV business feasibility was attested. Through MCS, they found good results for *NPV* and *IRR* for micro and mini photovoltaic plants with no remote consumption. The *DPB* was not so good, with investment return in a long term. Unfortunately, battery costs continue to make PV projects combined with battery banks unviable, as shown in this study. However, the current trend

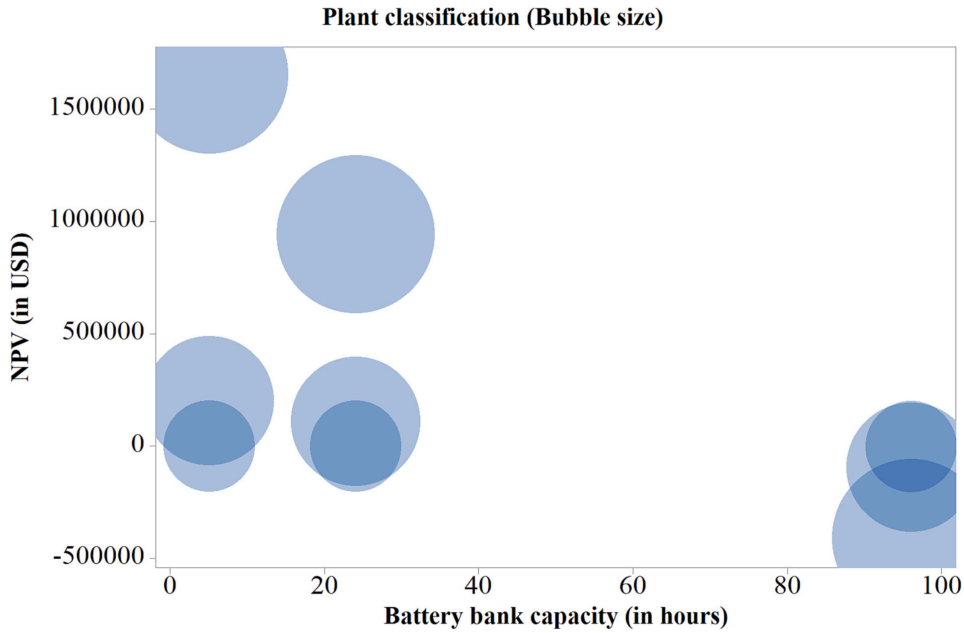

Fig. 8. Bubble Plot for NPV x Plant classification x Battery bank capacity (in hours).

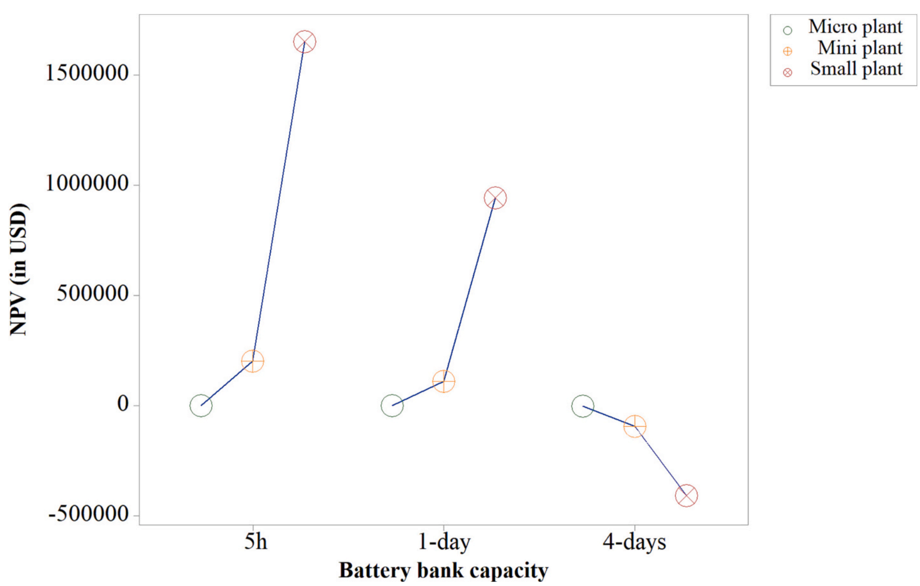

Fig. 9. Multi-vari chart for NPV by plant classification and battery bank capacity.

Table 6
Probability of economic viability by power plant classification 30 % 5 h, 50 % one day and, 20 % four days storage.

Output Classification	Using WT			Using CT			Difference WT-CT		
	NPV[a]	*IRR*[b]	*DPB*[c]	*NPV*[a]	*IRR*[b]	*DPB*[c]	*NPV*	*IRR*	*DPB*
Micro plant	52.17 %	26.08 %	0.67 %	47.97 %	23.62 %	0.87 %	4.20 %	2.46 %	−0.20 %
Mini plant	62.99 %	37.50 %	2.00 %	67.01 %	42.35 %	4.08 %	−4.02 %	−4.85 %	−2.08 %
Small plant	66.96 %	40.51 %	2.26 %	75.22 %	51.66 %	5.06 %	−8.26 %	−11.15 %	−2.80 %

[a] $P\ (NPV \geq 0)$.
[b] $P\ (IRR \geq 12\ \%)$.
[c] $P\ (DPB \leq 5$ years).

of reduction of battery costs is opening new prospects towards viability of these solutions in a near future.

The lack of regulation for ESS in Brazil and inadequate regulation and economic incentives for DG are the main barrier to the economic viability of such projects. In this study, it was proposed the use of battery banks for DG and three new classification sizes for distributed power plants. As demonstrated, even with these regulatory changes, DG with BESS is still economically unfeasible in some scenarios. New economic

Table 7
Comparison among previous studies.

Reference	Year	Scenario	Analysis	Investment	Tariffs	Results
Holdermann et al. [75]	2014	PV as DG	Deterministic	2508 €/kW	0.11 up to 0.22 €/kWh	Unfeasible
Rocha et al. [45]	2017	PV as DG	Stochastic	5827 up to 6427 $/kW	0.07 up to 0.15 $/kWh	Most unfeasible
Silva and Branco [30]	2018	PV + BESS	Deterministic	3539 $/kW	0.19 $/kWh	Unfeasible
Deotti et al. [31]	2020	PV + BESS	Deterministic	4410 R$/kW	0.53 up to 1.24 R$/kWh	Unfeasible
Doile et al. [55]	2021	PV as DG	Stochastic and Deterministic	1630 $/kW	0.22 up to 0.28 $/kWh	Feasible
Present study		PV as DG	Stochastic	777 up to 1630 $/kW	0.06 up to 0.42 $/kWh	Feasible
		PV + BESS	Stochastic	777 up to 2966 $/kW	0.06 up to 0.42 $/kWh	Most unfeasible for greater battery banks

regulation and economic incentives are recommended to make these projects viable. Such regulation and incentives must differentiate micro, mini and small generators, as proposed in this study. The smaller the project, the greater the incentive should be.

5. Conclusion

When studied the distributed PV system without battery banks the viability was attested. It is clear that for micro plant with distributed generation, that one predominantly residential, the option for white tariff is better than the conventional tariffs schemes. It happens due to high generation at off-peak time and high consumption at peak time. Another kind of economic incentives should be created for PV micro plant. As this segment has a very low consumption when compared to the country's total demand, the net metering of 100 % compensation could be maintained. The industrial demand is less at peak time because they stop production at that time or use own Diesel generation. In this pattern, the white tariff scheme does not affect the energy bill. The energy storage regulation is crucial to this segment.

When added battery banks as energy storage systems, the projects presented low probability of economic feasibility for battery banks with greater capacity. Cases with five-hours and 1-day battery banks capacity show themselves economically viable. However, cases with 4-days battery bank capacity show low probability of economic viability. The main problems, undoubtedly, are the battery price and the absence of economic incentives. Even, considering many scenarios with imported batteries at lower price, the projects still have a reduction in their probability of viability when compared with projects without battery banks. The battery storage systems introduction into the Brazilian electrical grid must be economically regulated and subsidized.

The last results considering the three battery bank sizes together show a lower probability of viability. Therefore, nobody will have economic reason to choose large battery banks. There is a double interest to reduce peak demand. On the one side, the government wants to reduce the dispatch of expensive power plants. On the other hand, consumers would like to reduce electricity bill by consuming their own produced energy during the peak time, when tariffs are high. For this reason, small battery banks for residential PV plants should be allowed and economically incentivised to reduce the undesirable peak demand.

All studied scenarios have considered the tax exemption in-force in 2022. Because of this, tax exemption may incentivize distributed photovoltaic plants, however, it is not enough to economically encourage the inclusion of energy storage systems at Brazilian power grid.

As the white tariffs scheme combined with energy compensation system are a problem for economic viability of distributed PV power plants, because the electricity production is in the out-off peak period, the insertion of another electricity source is suggested for future studies. This additional source must be able to produce electricity during the peak time.

Finally, despite its endogenous character, due to the input data, the study can serve as a basis for similar cases in other countries, especially those that still do not have regulations in force that allow the use of ESS. It should not be seen only as a feasibility study, but as an analysis to verify whether the regulation is being limiting or a barrier.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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CRediT authorship contribution statement

Gabriel Nasser Doyle de Doile: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Writing- original daft preparation, Writing- review and editing, Validation and Visualization. **Paulo Rotella Junior:** Conceptualization, Methodology, Formal Analysis, Writing- original daft preparation, Writing- review and editing, Validation, Visualization, Project Administration and Funding Acquisition. **Luiz Célio Souza Rocha**: Conceptualization, Methodology, Formal Analysis, Resources, Writing- review and editing, Visualization, and Project Administration. **Karel Janda:** Writing- Reviewing and Editing, Visualization, Funding Acquisition. **Rogério Santana Peruchi**: Conceptualization, Methodology, Formal Analysis, Investigation, and Visualization. **Giancarlo Aquila:** Methodology, Writing- Reviewing and Editing, and Visualization. **Pedro Paulo Balestrassi:** Writing- Reviewing and Editing, and Visualization.

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