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Impact of the net-metering policies on solar photovoltaic investments for residential scale: A case study in Brazil

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A R T I C L E I N F O

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A B S T R A C T

The adoption of renewable energy resources is in the core of energy transition. However, its implementation can be highly impacted by country policies. A limited number of researches investigated solar photovoltaic investments, comparing net-metering rules for distinctive energy consumption levels and different discounted rates, from the investors' point of view. This paper analyzes the impact of Brazilian net-metering rules on solar photovoltaic investments, considering residential scale. The methodology contemplates the development of a Discounted Cash Flow model to calculate Discounted Payback (*DP*), Net Present Value (*NPV*), Internal Rate of Return (*IRR*), and Levelized Cost of Electricity (*LCOE*) of projects. The case studies consider the impact of Brazilian regulation from net-metering rules (previous, considered, and current), energy consumption levels (Low, Middle, and High), and discount rates (5 %, 10 %, 15 %, and 20 %). The results show that from the previous to current rule the return for investor, on average, decreased 5.77 %. However, this reduction would be of 12.81 % if considered rule was adopted. For the 36 studies carried out, even in the worst case the investments remain viable. Therefore, the existing policy is suitable for the current stage of sector development; minimizing the impacts for energy tariff, distribution companies, consumers, and prosumers.

List of variables	
CF_n	Cash flow in the period n [R$]
C_n	Photovoltaic system costs in the period n [R$]
DCF_n	Discounted cash flow in the period n [R$]
DP	Discounted payback [years]
E_n	Energy generated by the photovoltaic system in the period n [kWh]
IRR	Internal rate of return [%]
$LCOE$	Levelized cost of electricity [R$/kWh]
n	Period or year of the DCF
n_{esp}	Smallest value of n for positive accumulated DCF
NPV	Net present value [R$]
List of parameters	
Ger_n	Average generation in the year n, considering surplus compensation [kWh]
I_0	Initial investment cost [R$]
$MARR$	Minimum attractive rate of return [%]
N	Number of periods considered
$O\&M_n$	Cost of operation and maintenance of the system in the year n [R$]
r	Discount rate [%]
Tar_n	Average energy tariff in the year n [R$/kWh]
α	Degradation rate of the photovoltaic system [%]
β	Readjustment rate of the energy tariff [%]
γ	Readjustment rate of the $O\&M$ costs [%]

1. Introduction

Distributed Generation (DG) using solar Photovoltaic (PV) increased 26 % worldwide in 2022. This was the largest absolute generation growth of all renewable sources in the year. Wind generation was surpassed for the first time in history. Some factors that contributed to this expansion include: development of the supply chain, increase in the economic attractiveness, and policy support. Policy support remains as the main driver for PV deployment in the world [1].

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DG refers to technologies that generate electricity at or near the place it is used. The distributed system may serve a single structure, as a home, or it may be part of a microgrid (smaller grid connected to a larger electricity delivery system), as an industrial facility. DG allows for reduction in transmission and distribution lines losses, improvement in grid stability/security, and reduction in the environmental impact of electricity generation. In the residential sector, common DG systems include solar PV and small wind turbines [2].

Solar PV uses cells to convert light from the sun in electricity. The PV cell consists of one or two layers of a semi conducting material, usually silicon. When the light strikes the cell, it creates an electric field across the layers causing electricity to flow. More light intensity results in greater flow of electricity. The basic component of solar PV technology is the cell. Multiple PV cells are connected to form a PV module or panel - the smallest PV component sold commercially. PV modules or panels can be arranged in groups to form a PV array [3].

There are three main types of solar PV systems: on-grid, off-grid, and hybrid. The on-grid systems are connected to the public electricity grid. These are the most common systems used by residential consumers. An off-grid system is not connected to the electricity grid and, therefore, it requires battery storage. The use cases include rural and remote areas. Hybrid systems are dependent on the grid and can also accumulate extra electricity in a storage unit. These are more suitable for the agricultural or residential sector [4].

The introduction of DG using solar PV systems connected on-grid creates a new relational structure between consumers and distribution companies - the flow of power becomes bidirectional. This results in challenges in grid management and control. The main point of concern is related to how consumption and generation flows are measured and billed, that is, what compensation mechanism is used. According to NREL [5], compensation mechanisms are defined as a reward to DG system owners for the electricity they self-consume and the excess that is exported to the grid.

NREL [5] affirms there are effectively three types of compensation mechanisms: net-metering, buy-all sell-all, and net-billing. In the net-metering mechanism, a consumer installs small generators in their residence, such as solar PV or wind turbine, and the energy generated is used to offset the unit's electricity consumption. When generation is greater than consumption, the positive energy balance can be used to reduce consumption in subsequent months. There is also the possibility for the consumer to use surplus generation in other units previously registered within the same distribution area [6].

In a buy-all sell-all mechanism, DG system owners buy all electricity from a company to consume and sell all electricity produced by their system. There is a standard sell rate for the electricity generated. In net-billing mechanism, DG system owners can consume electricity generated by their system in real time and export any generation in excess to the grid. However, different from net-metering, saving kilowatt-hours within a billing cycle to offset future consumption is not allowed. All net energy exported is metered and credited at a predetermined sell rate at the moment it is injected into the grid [5].

In Brazil, the compensation mechanism for DG systems is defined by the Brazilian Electricity Regulatory Agency (acronym in Portuguese, ANEEL). This organization is an independent federal agency in charge of supervising and regulating the electricity sector. Through Normative Resolution n° 482/2012, ANEEL regulated the net-metering, called Electric Energy Compensation System (EECS) in the country [7].

In the last decade, solar PV has increased exponentially in Brazil. Fig. 1 shows the evolution of solar PV installed power from Normative Resolution n° 482/2012 that allowed Brazilian consumers to generate their own electrical energy from renewable sources. According to Hansen & Zambra [8], the exponential growth of the solar PV in Brazil can be justified by incentive policies, stimulus for acquisition, and falling price of equipment. Other factors, such as rise in electricity tariff, can also contribute to solar PV adoption. Among incentive policies, net-metering is implemented in Brazil and it is the most adopted globally [9]. As stimulus for acquisition in the country, facilitated credit lines that aim to mitigate climate change, such as Climate Fund, can be cited [10]. Lastly, falling price of equipment due to drop in prices of key materials (as polysilicon) has favored the expansion of the solar source, as documented by NREL [11].

It is important to maintain growth of solar PV since the technology presents significant benefits to the environment and society in general. Solar PV contributes to the reduction of greenhouse gases emissions (i.e. decarbonization), allowing for deceleration of global warming (i.e. climate change). This is crucial especially for the 140 countries that have committed to net-zero target in Paris Agreement [12]. Moreover, DG from solar PV is an alternative for energy generation that implies lower investments on grid because it supplies local energy demand. Thus, it significantly impacts countries with emerging economy, such as Brazil, with large distances and absent or weak grid where it is expensive to extend or improve outdated transmission and distribution lines [13].

However, the fast penetration of solar PV creates complex scenarios, especially related to regulation. Net-metering rules impact PV system owners, non-PV system owners, and distribution companies. Under compensation can shift additional costs to PV system owners. Over compensation implies a loss of revenue for the distribution companies, transferring electricity costs for non-PV system owners. According to Iglesias & Vilaça [14], this may contribute to increased social inequality. The challenge is to create a model that results in a fair billing mechanism for participants while guaranteeing the growth of solar sector.

Therefore, the main motivation of this paper is the fact that net-metering rules affect attractiveness of solar PV investments. These rules can encourage or discourage solar PV adoption, altering pace for

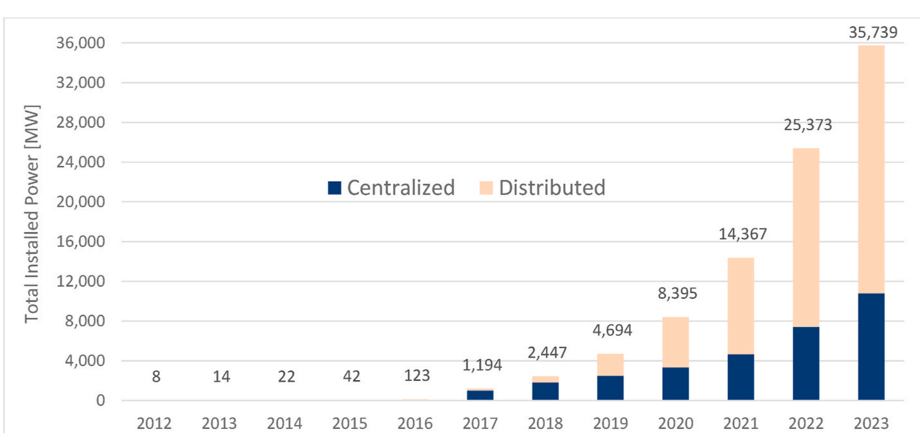

Fig. 1. Evolution of the PV installed power in Brazil from 2012 [25].

energy transition. Thus, understanding how profitability of solar PV investments is impacted by the compensation mechanisms is crucial for countries' sustainable development.

The expansion of solar PV led to numerous studies focused on net-metering in many countries, such as China [15], United States [16], Japan [17], India [18], and Germany [19]. A review on solar energy policy for all of these countries was presented in Minazhova et al. [20]. Considering the topics "net-metering", "solar photovoltaic", and "Brazil"; in the last five years the following authors published their findings: Vieira & Carpio [21], Drumond Jr. et al. [22], Santos & Lucena [23], Costa et al. [24], Iglesias & Vilaça [14], Komeno et al. [9], and Pinto et al. [25].

Santos & Lucena [23] evaluates the influence of climate change on the technical-economic potential of PV systems in the residential sector. Pinto et al. [25] assesses the benefits of a battery energy storage system on the financial attractiveness of PV generation in public buildings. Although these two studies evaluate the economic viability of PV investments and are related to net-metering, their focus is not towards compensation mechanism.

Vieira & Carpio [21] analyzes the economic impact on residential fees under transition to distributed PV systems connected to grid. Komeno et al. [9] explores the economic impact of net-metering rules for solar PV systems. Costa et al. [24] presents the socioeconomic and environmental consequences of the current compensation rule in 35 Brazilian concession areas. These three studies are focused on the impact of net-metering on PV systems. However, their point of view is for non-PV adopters and/or distribution companies.

Drumond Jr. et al. [22] investigates the impact of fiscal and tariff incentives on the economic viability for a residential PV system in 35 distribution companies. Iglesias & Vilaça [14] studies the effect of the previous and current net-metering rules on technical-economic aspect of PV systems. The first one applies *DP* and *NPV*; while the second employs *DP*, *LCOE*, and cost/benefit. Both of them perform assessments for a single discount rate and energy consumption characteristic.

Therefore, although the impact of the net-metering rules on solar PV projects has been the subject of these studies, there is a gap in further evaluating diverse scenarios in the Brazilian context from the PV system owner's point of view. As an example, the application of viability indicators and variation of discount rates and energy consumption levels have been neglected in previous studies. Diverse scenarios can provide broader information on the topic, resulting in better fitting within the global context for adequate comparisons or implementations for countries with objectives similar to Brazil (of reducing incentives as solar PV installed capacity becomes more substantial). Besides, wider coverage benefits scientific community, as well as, policy makers, regulatory agencies, and end consumers supporting their decision-making.

Brazil is an important case study for several reasons. According to ANEEL [26], almost 85 % of Brazil's electrical matrix comes from renewable sources. This makes the country stand out as an international reference. In 2023, Brazil placed the 6th country in the world rank in terms of solar energy capacity after China, United States, Japan, Germany, and India [27]. Its geographical location (almost entirely within the tropical zone) allows for high solar irradiation, with a daily incidence that can range from 4500 to 6300 Wh/m^2. This contributes to great potential for solar PV in the country [28].

In this circumstance, and considering the climate change discussions that drive energy transition, this paper evaluates the impact of the net-metering policies on PV investments. The main EECSs presented in Normative Resolution n^o 482/2012, Regulatory Impact Analysis n^o 003/2019, and Law n^o 14.300/2022 (previous, considered, and current) are investigated. Their influence is analyzed from the investor's point of view, considering residential units with different levels of consumption (Low, Middle, and High). The methodology is based on the creation of a discounted cash flow model and four economic and financial viability indicators (*PD*, *NPV*, *IRR*, and *LCOE*), covering discounted rates appropriate to the country's economic indices (5 %, 10 %, 15 %, and 20 %). In total, 36 scenarios are examined.

The main contributions from this paper contemplate: (i) a mathematical model for evaluating the economic viability of solar PV investments, from PV system owners' point of view, that can be adapted and employed worldwide; (ii) a historical background that describes the evolution of solar PV regulation in Brazil; (iii) a detailed analysis of the impact of different net-metering rules for solar PV attractiveness based on Brazilian experience; and (iv) a full exploration of the variation of *PD*, *NPV*, *IRR*, and *LCOE* for 36 investigated scenarios that includes different discount rates and consumption levels which have shown significant impact on results.

The remainder of this article is structured as follows: Section 2 describes the background information on the PV regulation. Section 3 shows the development of the mathematical model employed. Section 4 presents the data of the consumer units, PV systems, scenarios, and model parameters. Section 5 shows the results and discussion considering different consumer units projects, discount rates, and net-metering policies. Finally, Section 6 brings key findings, comparison with previous studies, and economic/policy/social implications. Lastly, Section 7 presents conclusions, limitations, and future works.

2. Background

The policy related to DG has gone through numerous modifications in Brazil. The regulation started with the publication of Normative Resolution n^o 167/2005 which established conditions for purchasing and selling energy [29]. Then, Normative Resolution n^o 414/2010 (updated by Normative Resolution n^o 1000/2021), among other things, defined rights and duties of consumers and distributors [30]. After that, several Public Consultations, Public Hearings, Normative Resolutions, Regulatory Impact Analysis, Law Projects, and Laws were published in order to adjust rules.

Public Consultation n^o 15/2010 and Public Hearing n^o 42/2011 were held to discuss a legal provision, seeking to reduce barriers for installation of DG systems. The result was Normative Resolution n^o 482/2012 that defined the Electric Energy Compensation System (EECS) and Micro and Mini Distributed Generation (MMDG). The EECS is as an arrangement in which the energy injected by a consumer unit with MMDG is transferred as a free loan to the local distributor and subsequently compensated with its own electrical energy consumption. The MMDG was established as microgeneration systems up to 100 kW and minigeneration systems from 100 kW to 1 MW [7].

Normative Resolution n^o 482/2012 established a revision process. The new versions were Normative Resolution n^o 517/2012, n^o 687/2015, and n^o 786/2017. Normative Resolution n^o 517/2012 essentially changed legal aspects related to the energy transfer from the consumer to the grid. Normative Resolution n^o 687/2015 and n^o 786/2017 mainly aimed to improve topics related to the installed power limits and the modalities of participation [7].

Normative Resolution n^o 687/2015 changed the power limit of microgeneration for up to 75 kW and of minigeneration for greater than 75 kW and less than or equal to 3 MW for hydraulic sources and up to 5 MW for other renewable sources. Furthermore, new modalities for participation in the EECS were created in addition to local self-consumption: multiple consumer units, shared generation, and remote self-consumption. Normative Resolution n^o 786/2017 changed the minigeneration to greater than 75 kW and up to 5 MW and prohibited the inclusion of existing generating plants in the EECS [31,32].

The most updated regulation, Normative Resolution n^o 1059/2023, revokes Normative Resolution n^o 482/2012, n^o 517/2012, 687/2015, and 786/2017. As can be observed, the revisions did not change the net-metering in terms of compensation. However, this was the most critical point to be altered. Therefore, the Brazilian Electricity Regulatory Agency (ANEEL) published two documents with suggestions for alteration: Regulatory Impact Analysis n° 0004/2018 and n° 003/2019. In 2022, with the creation of the Law n° 14.300/2022 based on Law Project n° 5829/2019 a partial compensation mechanism was established [33].

In order to understand the net-metering in Brazil, it is important to describe the structure of the electricity tariff. The electricity tariff is composed by two main parts called: Distribution System Use Tariff (TUSD) and Energy Tariff (TE). Table 1 shows each component of the electricity tariff used by ANEEL in Technical Note n° 0062/2018 [33].

TUSD represents around 50 % of the total electricity tariff. It refers to the remuneration of the transmission and distribution utility companies and it is formed by four components. Distribution Line (28 %) represents regulatory costs for the use of assets of the distribution companies. Transmission Line (6 %) consists of regulatory costs for the use of assets of the transmission companies. Charges (8 %) characterizes the costs related to the electricity distribution service. Losses (8 %) recovers network costs with technical and non-technical losses [34].

TE is responsible for the other 50 % of electricity tariff. It corresponds to the charges for the energy consumed in the month. TE is formed by two components. Charges (12 %) represents costs of service, reserved energy (that ensures the supply of energy to the National Interconnected System), and contribution on the use of water resources (which is legal obligation of producers of electricity from water sources). Energy (38 %) recovers the costs of purchasing electricity for resale to the consumer [34].

It is important to note that the percentages listed in Table 1 are average values. The value of Distribution Line, for example, is calculated according to the local power distribution company and number of consumers served by the company in the area. For some entities, such as Greener, Distribution Line is equal to 30.8 % [35].

EECS alternatives are distinguished by the way they value the energy injected into the grid. The regulation established by Normative Resolution n° 482/2012 determined that all components of the electricity tariff are considered. In this case, 100 % of the energy injected is compensated. This means that 1 kWh of energy injected into the grid would generate 1 energy credit [7].

The rule proposed by ANEEL in Regulatory Impact Analysis n° 003/2019 would compensate only one part of the electricity tariff, TE Energy. For this situation, approximately 38 % of the energy injected would be compensated [36].

Lastly, Law n° 14.300/2022 is structured depending on the date the consumer joined the EECS, as follows [37]:

- before 2023: all electricity tariffs are compensated until 2045.
- from 2023 to 2028: seven years of gradual payment (15 %–90 %) of the TUSD Distribution Line - 28 % (that corresponds to around 100 %–28 % = 72 %).
- after 2029: compensation will be defined by ANEEL after valuing the benefits of DG.

The net-metering presented in Normative Resolution n° 482/2012 (EECS = 100 % compensation), Regulatory Impact Analysis n° 003/2019 (EECS = 38 % compensation), and Law n° 14.300/2022 (EECS = 72 % compensation) are investigated in this research. They correspond to the previous, considered, and current EECS in Brazil.

Table 1
Components of the electricity tariff and average percentage weight.

Distribution System Use Tariff (TUSD)				Energy Tariff (TE)	
Distribution Line 28 %	Transmission Line 6 %	Charges 8 %	Losses 8 %	Charges 12 %	Energy 38 %

3. Methodology

Usually, the economic consideration of a project is based on the expected financial return on the investment. Economic engineering deals with the main methods used to analyze investment projects. Therefore, it helps decision-making about investment alternatives. Since this research considers the time value of money, the concept of Discounted Cash Flow (*DCF*) is applied. In this case, the estimated Cash Flows (*CFs*) are discounted at a rate, r [%]. The objective is to bring the nominal values of each period to the present, according to Equation (1).

For r, the country's main economic indices, such as national consumer price index and general market price index can be employed. DCF_1, DCF_2, …, DCF_N correspond to the present value of CF_1, CF_2, …, CF_N; respectively. N is the total number of periods and n is the specific period considered [38].

$$DCF_n = \frac{CF_n}{(1+r)^n} \tag{1}$$

DCF is widely used to evaluate projects, assets or companies. Therefore, it is the basis for decisions of investment, acquisition or business merger. All viability indicators that use the *DCF* require an accurate estimate of future *CFs*.

The methodology includes the development of a mathematical model to calculate the viability indicators of solar PV investments. Among the indicators, the following stand out: Discounted Payback (*DP*), Net Present Value (*NPV*), Internal Rate of Return (*IRR*), and Levelized Cost of Electricity (*LCOE*).

3.1. Viability indicators

3.1.1. Discounted Payback (DP)

DP is used to calculate the number of periods (years, months, weeks, etc.) required for a project to return the initial capital invested [39]. It corresponds to the value of n (specific period) when the sum of the *DCFs* is equal to the value of the initial investment, I_0 or DCF_0, as Equation (2).

$$\sum_{n=1}^{DP} DCF_n = |DCF_0| \tag{2}$$

The lower the *DP*, the more liquid the investment and therefore less risky. This indicator considers the time value of money, but does not consider the *CFs* after the payback period. *DP* can be obtained according to Equation (3), where n_{esp} corresponds to the smallest value of n for positive accumulated *DCF*.

$$DP = (n_{esp} - 1) + \frac{\left|\sum_{n=0}^{n_{esp}-1} DCF_n\right|}{\left|\sum_{n=0}^{n_{esp}-1} DCF_n\right| + \sum_{n=0}^{n_{esp}} DCF_n} \tag{3}$$

For example, for an initial investment of R$ 50,000.00, with constant annual return of R$ 14,000.00, and discount rate equal to 10 %; Table 2 shows *CF*, *DCF*, and accumulated *DCF*, considering 10 years. According

Table 2
CF, *DCF*, and accumulated *DCF*.

Year	*CF*	*DCF* (10 %)	accumulated *DCF*
0	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00
1	R$ 14,000.00	R$ 12,727.27	-R$ 37,272.73
2	R$ 14,000.00	R$ 11,570.25	-R$ 25,702.48
3	R$ 14,000.00	R$ 10,518.41	-R$ 15,184.07
4	R$ 14,000.00	R$ 9562.19	-R$ 5621.88
5	R$ 14,000.00	R$ 8692.90	R$ 3071.01
…	…	…	…
10	R$ 14,000.00	R$ 5397.61	R$ 36,023.94

to this table, the invested capital will be returned between the fourth and fifth years, more specifically, in 4.65 years (calculated in the sequence).

$$DP = (5-1) + \frac{|-5,621.88|}{|-5,621.88| + 3,071.01} = 4.65$$

3.1.2. Net Present Value (NPV)

NPV is used to calculate, in terms of present value, the value of a project, asset or company. It is the difference between the present value of cash inflows and the present value of cash outflows over a period of time [39].

The higher the *NPV*, the more profitable the investment. An investment with $NPV > 0$ has revenues greater than expenses. If $NPV < 0$, expenses are greater than revenues. When $NPV = 0$, revenues and expenses are equal and the decision to invest in the project becomes neutral. *NPV* considers the time value of money and the *CFs* after payback. However, it is defined in terms of absolute value (monetary units), that is, it does not consider the scale of the project, in terms of size and duration. *NPV* consists of the sum of investment's *DCF*s, Equation (4).

$$NVP = \sum_{n=0}^{N} DCF_n \tag{4}$$

For the data in Table 2, *NPV* is equal to R$ 36,023.94. This value corresponds to the sum of the values from the *DCF* column (third column), which is equal to the value of the accumulated *DCF* in the last period (tenth row and fourth column).

3.1.3. Internal Rate of Return (IRR)

IRR is used to evaluate the percentage of profitability from a project. It represents the discount rate, *r*, which resets the *NPV* of the cash flows of an investment, in other words, it makes the present value of the inflows equal to the present value of the outflows. Therefore, *IRR* presents the reversal point of the investment decision, since it is expected, at least, that the return of a project is equal to its cost. *IRR* is the average intrinsic rate of return that the investor obtains, in each period, for the values of a *CF* considering $NPV = 0$ [39], as Equation (5).

$$\frac{CF_0}{(1+IRR)^0} + \frac{CF_1}{(1+IRR)^1} + \frac{CF_2}{(1+IRR)^2} + \ldots + \frac{CF_N}{(1+IRR)^N} = 0 \tag{5}$$

The higher the *IRR*, the more profitable the investment. Considering the minimum attractive rate of return (*MARR*), an investment with $IRR > MARR$ is considered attractive. If $IRR = MARR$ the investment is neutral. When $IRR < MARR$ the return on investment is lower than what the company's partners or shareholders require for the application of equity.

IRR considers the time value of money, the *CFs* after payback and is defined in terms of relative value (expressed as a percentage), that is, it considers the scale of the project. As a disadvantage, *IRR* assumes that all flows (revenue and expenses) are discounted at the same rate.

There is no algebraic formula to calculate *IRR* directly. Its calculation involves solving polynomial equations. An alternative is to apply the interpolation method, Equation (6), for two discount rates, final and initial (r_f and r_i), whose interval contains the *IRR*, considering the respective *NPVs*.

$$IRR = \left[r_i + (r_f - r_i) \times \left(\frac{NPV_i}{NPV_i - NPV_f} \right) \right] \times 100 \tag{6}$$

For example, Fig. 2 shows the graph *NPV* versus *r* for the data in Table 3, varying the discount rate from 0 to 100 %. As discount rate increases, *NPV* decreases. *IRR* is between 20 % and 30 %, since when *NPV* crosses the *x* axis its value is equal to 0.

Table 3 extends Table 2, displaying the *NPV* (accumulated *DCF*) for the 20 % and 30 % discount rates, interval that contains the *IRR*. *IRR* value for the example is 25.64 % (calculated in the sequence).

$$IRR = \left[0.2 + (0.3 - 0.2) \times \left(\frac{8,694.61}{8,694.61 - (-6,718.45)} \right) \right] \times 100 = 25.64\%$$

3.1.4. Levelized Cost of Electricity (LCOE)

LCOE can be used as a metric to compare different proposals of solar PV systems. It represents the cost to generate a unit of electrical energy from a given system, while the energy tariff represents the cost of purchasing a unit of electrical energy from a specific company [39].

LCOE corresponds to the ratio between the *NPV* of the costs of a generation asset (I_0 + *O&M* costs) and the energy generated by the system during its lifetime. In Equation (7), C_n corresponds to the system costs in the period *n* and E_n refers to the energy generated by the system also in the period *n*.

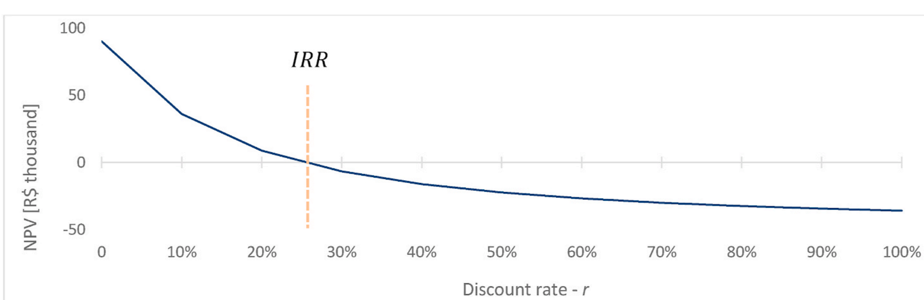

Fig. 2. Graph *NPV* versus *r* for the data in Table 3.

Table 3
NPV for the 20 % and 30 % discount rates.

Year	*CF*	*DCF* (20 %)	*NPV*	*DCF* (30 %)	*NPV*
0	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00
1	R$ 14,000.00	R$ 11,666.67	-R$ 38,333.33	R$ 10,769.23	-R$ 39,230.77
2	R$ 14,000.00	R$ 9722.22	-R$ 28,611.11	R$ 8284.02	-R$ 30,946.75
3	R$ 14,000.00	R$ 8101.85	-R$ 20,509.26	R$ 6372.33	-R$ 24,574.42
4	R$ 14,000.00	R$ 6751.54	-R$ 13,757.72	R$ 4901.79	-R$ 19,672.63
5	R$ 14,000.00	R$ 5626.29	-R$ 8131.43	R$ 3770.61	-R$ 15,902.02
…	…	…	…	…	…
10	R$ 14,000.00	R$ 2261.08	R$ 8694.61	R$ 1015.53	-R$ 6718.45

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=0}^{N} E_n} \tag{7}$$

For example, suppose that the *LCOE* of an asset is estimated at 0.56 R$/kWh while the company charges 0.70 R$/kWh for the energy tariff. In this case, the investor can generate their own energy for a value of at least 20 % lower than that offered by the distributor.

As a limitation of the *LCOE*, it should be noted that the cost considered is not equivalent to value. The lower cost shown may be associated with a lower quality system or service. Therefore, like the other viability indicators, *LCOE* should not be used as the only metric.

3.2. Mathamatical model

The proposed mathematical model consists of the development of a *DCF* for the investment. For solar PV systems, the *DCF* assumes as input the net revenue (saved cost) due to the energy generated by the system, Ger_n. $(1 - \alpha)$. Tar_n. $(1 + \beta)$. For the first factor of this product, the calculation involves the energy generated, consumed, injected into the grid, and compensated by the system. The net revenue contemplates the energy consumed and compensated, that is, the benefits brought by the system. The output corresponds to expenses with maintenance, system insurance, and inverter replacement, $O\&M_n$. $(1 + \gamma)$.

The *DCF* considers the time value of money. Therefore, the estimated *CFs* are discounted at a rate, *r*. The objective is to bring the nominal values of each period to the present, Equation (8). Details about data, scenarios, parameters, and other assumptions are described in the next section.

$$DCF_n = \frac{Ger_n \,.(1-\alpha)\,.Tar_n\,.(1+\beta) - O\&M_n\,.(1+\gamma)}{(1+r)^n} \tag{8}$$

where:

n	period or year of the *DCF*;
Ger_n	average PV generation in the year n, considering surplus compensation [kWh];
α	degradation rate of the PV system [%];
Tar_n	average energy tariff in the year n [R$/kWh];
β	readjustment rate of the energy tariff [%];
$O\&M_n$	cost of maintenance and insurance of the system in the year n [R$];
γ	readjustment rate of the *O&M* costs [%];

From Equation (8), it is possible to calculate *DP*, *NPV*, *IRR*, and *LCOE* viability indicators in equations (3), (4), (6) and (7); respectively. *DP* and *IRR* can be calculated as Tables 2 and 3, considering the *DCF* defined in Equation (8) for solar PV investments. Since $DCF_0 = I_0$, *NPV* in Equation (4) can be rewritten as Equation (9).

$$NPV = -I_O + \sum_{n=1}^{N} \frac{Ger_n \,.(1-\alpha)\,.Tar_n\,.(1+\beta) - O\&M_n\,.(1+\gamma)}{(1+r)^n} \tag{9}$$

From Equations (8) and (9), *LCOE* viability indicator in Equation (7) can be rewritten as Equation (10). In this equation, C_n includes the costs of initial investment and operation/maintenance of the system; *En* corresponds to the average solar PV generation in the year *n* for the EECS.

$$LCOE = \frac{I_0 + \sum_{n=1}^{N} \frac{O\&M_n}{(1+r)^n}}{\sum_{n=0}^{N} Ger_n} \tag{10}$$

4. Data

The case studies are carried out according to the data described in Sections 4.1 to 4.4. These sections present the data related to (4.1) consumer units, (4.2) PV systems, (4.3) scenarios, and (4.4) model parameters.

4.1. Consumer units

Three consumer units located in the state of Sao Paulo were chosen as study object. Their consumption levels are classified in this study as low, middle, and high. These consumer units have an energy supply contract with Companhia Piratininga de Força e Luz (CPFL). They belong to Group B1 of consumers, served at residential voltage (less than or equal to 25 kW).

Table 4 presents the extreme and average values for the year of highest consumption of each unit, considering the last five years. It contains the minimum, maximum, and average values of consumption [kWh]. These data, provided by the distribution company, are important for sizing the PV systems.

4.2. PV systems

For each consumer unit a PV system configuration was defined in 2023 by specialized company in services, equipment, labor, and installation materials of PV systems; using a commercial software. The proposals consider an on-grid PV system, panels installed facing the north and inclination of 20° to prevent dust from accumulating.

The technical specifications and acquisition cost of the PV systems for each consumer unit are presented in Table 5. Considering the data provided (average monthly generation and area) and an average insolation of 5000 Wh/m^2 it is possible to estimate the efficiency of the systems at approximately 16 %, as Villalva [41].

4.3. Scenarios

Sensitivity analysis relates to uncertainties in the input variables or parameters of a model used for decision making. In order to check the sensitivity of a model, variables or parameters that significantly influence the results are chosen so that the effect of their changes on the results is observed [38].

The economic viability of PV investments is examined for the three EECSs presented in Section 2: previous (EECS = 100 %), current (EECS = 72 %), and considered (EECS = 38 %). For each of them, three consumer units (Low, Middle, and High) and four discount rates (5 %, 10 %, 15 %, and 20 %) are considered.

For the four chosen discount rates, three main economic indices in Brazil were used. These indices were employed due to their importance for the national economy. They are known as IPCA, IGP-M, and SELIC.

- The Extended National Consumer Price Index (acronym in Portuguese: IPCA) measures the price variation of a range of goods and services consumed by the population, considering the weight they have on family budget [42].
- The General Price Index - Market (acronym in Portuguese: IGP-M) measures the variation in prices of goods, services, and raw materials used in agricultural, industrial, and civil construction production [43].
- The Special Settlement and Custody System (acronym in Portuguese: SELIC) refers to the interest rate determined in one-day loan

Table 4
Minimum, maximum, and average energy consumption of the three units.

Consumption [kWh]	Low	Middle	High
Minimum	170	349	765
Maximum	318	684	1187
Average	235	463	1003

Table 5
PV project data for the three consumer units.

Technical and cost data	Low	Middle	High
Nominal power [kWp]	2.20	4.40	8.80
Number of modules	4	8	16
Estimated area [m^2]	11	22	44
Estimated average monthly generation [kWh]	264.00	528.00	1104.00
Total cost of system [R$]	10,290.52	17,424.07	28,023.18
Cost/Power [R$/Wp]	4.68	3.96	3.18

operations among financial institutions that use public bonds of the National Treasury as collateral. It is the economy's basic interest rate [44].

Fig. 3 shows historical data (2010–2023) and projection (2024–2026) of the IPCA, IGP-M, and SELIC in Brazil; extracted from IBGE [42], FGV [43], and BCB [44]. The average of the data in this figure for the three indices is 7.31 %. Considering the highest value of each index (IPCA: 10.67 %, IGP-M: 23.14 %, and SELIC: 14.15 %) the average is 15.99 %. Therefore, for the discount rates, multiples of 5 were adopted, which include the mentioned averages of 7.31 % and 15.99 %; justifying the selected values of 5 %, 10 %, 15 %, and 20 %.

In total, the combination of three EECSs, three consumer units, and four discount rates, results in 36 analyzed scenarios, presented in Table 6.

4.4. Model parameters

As can be seen in Equations (8)–(10), studies of economic viability depend on several parameters. These include period considered for the analysis [years], degradation rate of the PV system [%], adjustment rate of the energy tariff [%], *O&M* costs related to the initial investment [%], and readjustment rate of the *O&M* costs [%].

In regards to the period considered for the analysis, NREL [45] estimates the useful life of PV systems to be approximately 25–40 years depending on various factors, such as environmental conditions. As far as the productive life of a solar panel, modules are typically warrantied for 20–25 years, after which they can still produce electricity, but the level of actual output is no longer guaranteed. Thus, the period considered for the analysis, [N], is 25 years.

In relation to the degradation rate of PV systems, NREL [46] has shown that solar panels present an average performance reduction rate of around 0.5 % per year, which can be higher in hot climates. Rocha et al. [47], Vale et al. [48], Fontoura et al. [49], and Giovanini et al. [50] adopt a value between 0.7 % and 0.8 % for annual loss of module efficiency. Considering these researches, 0.7 % is used as the degradation rate of the PV systems, [α].

For the adjustment rate of the energy tariff, it is possible to consult the values from 2018 to 2022 for CPFL Piratininga consumers at CPFL [51]. Considering the readjustments of the last five years (18.70 %, −11.28 %, 8.95 %, 16.40 %, and 9.60 %) for Group B participants, the average annual rate [β] adopted is 8.47 %.

The operation and maintenance costs with PV systems are estimated not to exceed 1 % per year of the total invested value. As in Holdermann et al. [52] and Rocha et al. [47], in this research 0.5 % of the initial investment is used as value for *O&M* costs. In relation to the readjustment rate of the *O&M* costs, [γ], the value of 0.1 % is adopted.

The fixed parameters for the 36 scenarios evaluated are listed in Table 7. Based on the recent effective cost of the energy tariff from the consumer units, the value of 0.88 R$/kWh was adopted as the initial energy tariff.

5. Results and discussion

The results and discussion are organized in four sub-sections. Sub-section 5.1 presents *IRR*, *LCOE*, *DP*, and *NPV* of the consumer unit projects (Low, Middle, and High) for the three EECSs (100 %, 72 %, and 38 %). In this sub-section, the relationship between PV projects and viability indicators is assessed. In Sub-section 5.2, the effect of the four discount rates adopted (5 %, 10 %, 15 %, and 20 %) on *DP* and *NPV* is analyzed, considering extreme scenarios. In Sub-section 5.3 the impact of the net-metering policies on the viability of PV investments is examined, showing the variation in *IRR*, *LCOE*, *DP*, and *NPV* from the evaluated scenarios. Lastly, Sub-section 5.4 shows how the results differ

Table 6
Scenarios for studying economic viability of PV systems (3 × 3 × 4 combinations = 36 scenarios).

Net-metering	Consumption	Discount Rate (r)
Previous (EECS = 100 %)	Low, Middle, High	5 %, 10 %, 15 %, 20 %
Current (EECS = 72 %)	Low, Middle, High	5 %, 10 %, 15 %, 20 %
Considered (EECS = 38 %)	Low, Middle, High	5 %, 10 %, 15 %, 20 %

Table 7
Parameters for calculating *DCFs*.

Description	Variable	Value
Number of years considered for the analysis	N	25 years
Degradation rate of the PV systems	α	0.7 %
Adjustment rate of the energy tariff	β	8.47 %
Annual cost of system maintenance in relation to I_0	*O&M*	0.5 %
Adjustment rate of the *O&M* costs	γ	0.1 %

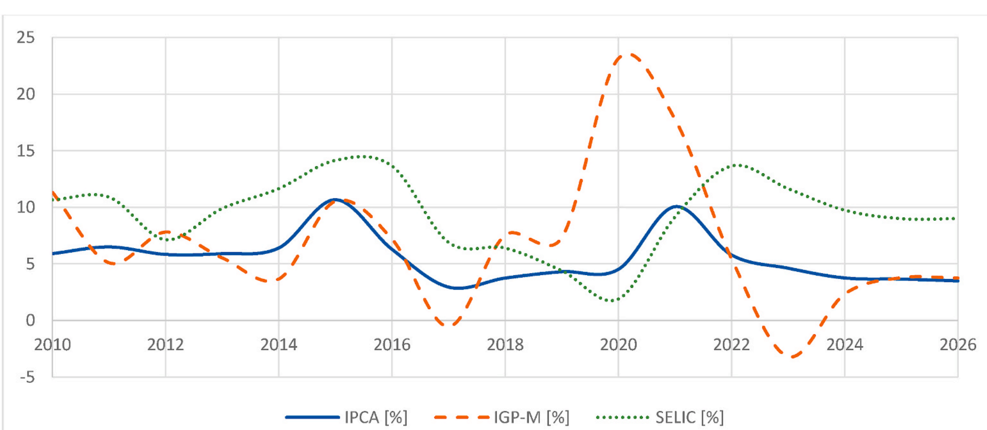

Fig. 3. Historical data (2010–2023) and projection (2024–2026) of the IPCA, IGP-M, and SELIC.

across different energy consumption levels, discount rates, and compensation systems for the most current and probable variables.

5.1. Consumer unit projects (low, middle, and high)

Tables 8–10 present the results from the 36 chosen scenarios, showing the viability indicators of the consumer unit projects (Low, Middle, and High) for previous, current, and considered EECSs (100 %, 72 %, and 38 %). For *IRR* and *LCOE* average values are presented, while for *DP* and *NPV* the four discount rates adopted in this research (5 %, 10 %, 15 %, and 20 %) are considered.

The results show that project High is the most profitable, followed by project Middle, and then by project Low. The interpretation of the results is associated with the technical and cost data of the projects presented in Table 5. This table shows that the cost/power ratio [R$/Wp] is lowest for project High, followed by project Middle, with project Low being the one with the highest cost per Wp. Therefore, as expected, in Tables 8–10 *IRR* decreases in the order High-Middle-Low; while *LCOE* and *DP* increase in the same order.

Table 5 also shows that the total cost of system [R$] is lower for project Low, followed by project Middle, with project High being the one with the highest total installation cost. As explained in Section 3, *NPV* is defined in terms of absolute value, that is, this indicator is biased towards presenting a higher *NPV* for projects with large initial investment, even if they are not better in relative terms. Thus, in Tables 8–10, *NPV* increases in the order Low-Middle-High.

Considering the most optimistic and pessimistic scenarios from the investor's point of view (EECS = 100 % with $r = 5$ % and EECS = 38 % with $r = 20$ %), Tables 8–10 shows that:

- For project Low, *IRR* varies from 34 % to 30 %, *LCOE* ranges from 0.15 R$/kWh to 0.17 R$/kWh, *DP* increases from 3.80 years to 7.34 years, and *NPV* decreases from R$ 80,634.19 to R$ 7335.75.
- For project Middle, *IRR* varies from 39 % to 34 %, *LCOE* ranges from 0.12 R$/kWh to 0.15 R$/kWh, *DP* increases from 3.23 years to 5.75, and *NPV* decreases from R$ 164,649.94 to R$ 17,906.94.
- For project High, *IRR* varies from 49 % to 42 %, *LCOE* ranges from 0.10 R$/kWh to 0.11 R$/kWh, *DP* changes from 2.50 years to 4.05, and *NPV* decreases from R$ 353,275.27 to R$ 46,059.74.

It is worth highlighting that *IRR* value for the project High in the most pessimistic scenario (Table 10), 42 %, is higher than the *IRR* for the project Low even in the most optimistic scenario, 34 % (Table 8). It also happens for the other viability indicators (*LCOE*, *DP*, and *NPV*), as long as the same discount rate is adopted. This shows how important the project characteristics are in the viability analysis.

Table 11 presents the percentage variation of the viability indicators previously listed. For each viability indicator, the direction of the vertical arrows specifies whether the change corresponds to an increase or decrease in the variable. As can be seen, the percentage variation of the *IRR* increases in the order Low-Middle-High, while for *DP* and *NPV* it decreases in the same order. There is no significant change for *LCOE* indicator.

According to Table 11, the percentage variation of *IRR*, *LCOE*, *DP*, and *NPV* for extreme scenarios presents high mean values, being the smallest equal to 12.81 % and the largest equal to 89.00 %. Therefore, project characteristics, discount rates, and EECSs significantly affect the analysis of PV investments.

5.1.1. Discount rates (5 %, 10 %, 15 %, and 20 %)

Figs. 4 and 5 illustrate the *DP* variation, considering $r = 5$ %, 10 %, 15 %, and 20 % by consumer unit project, for EECS = 100 % (Normative Resolution n° 482/2012) and EECS = 38 % (Regulatory Impact Analysis n° 03/2019); respectively. The objective is to evaluate the impact of the discount rates on the *DP* for extreme scenarios (Tables 8 and 10).

From the data in Figs. 4 and 5, Table 12 presents the percentage increase in *DP* value of each project, considering the variations in discount rate. It is noted that for the system with greater compensation (EECS = 100 %) the percentage increases in *DP* are smaller than for the system with limited compensation (EECS = 38 %). That means, the lower the energy compensation, the greater the impact of the discount rate on the viability analysis. On average, changing the discount rate from 5 % to 10 %, 15 %, and 20 % impacts the *DP* value by 11.55 %, 26.11 %, and 46.09 %; respectively.

Figs. 6 and 7 illustrate the *NPV* variation, considering $r = 5$ %, 10 %, 15 %, and 20 % by consumer unit project, for EECS = 100 % (Normative Resolution n° 482/2012) and EECS = 38 % (Regulatory Impact Analysis n° 03/2019); respectively. Similar to what was done previously, the objective is to evaluate the impact of the discount rates on the *NPV* for extreme scenarios (Tables 8 and 10).

From the data in Figs. 6 and 7, Table 13 presents the percentage

Table 8
Results for previous alternative (EECS = 100 %).

Consumption		Low	Middle	High
IRR [%]		34	39	49
LCOE [R$/kWh]		0.15	0.12	0.10
$r = 5$ %	*DP* [years]	3.80	3.23	2.50
	NPV [R$]	80,634.19	164,649.94	353,275.27
$r = 10$ %	*DP* [years]	4.27	3.58	2.72
	NPV [R$]	39,034.73	81,370.79	178,932.38
$r = 15$ %	*DP* [years]	4.88	4.01	2.98
	NPV [R$]	20,180.01	43,619.62	99,887.00
$r = 20$ %	*DP* [years]	5.73	4.58	3.30
	NPV [R$]	10,615.89	24,467.21	59,776.68

Table 9
Results for current alternative (EECS = 72 %).

Consumption		Low	Middle	High
IRR [%]		32	37	46
LCOE [R$/kWh]		0.16	0.13	0.10
$r = 5$ %	*DP* [years]	4.08	3.47	2.69
	NPV [R$]	74,218.21	151,817.98	326,444.82
$r = 10$ %	*DP* [years]	4.62	3.87	2.94
	NPV [R$]	35,549.03	74,399.38	164,355.80
$r = 15$ %	*DP* [years]	5.33	4.37	3.24
	NPV [R$]	18,023.65	39,306.90	90,869.51
$r = 20$ %	*DP* [years]	6.36	5.03	3.60
	NPV [R$]	9134.54	21,504.51	53,581.93

Table 10
Results for considered alternative (EECS = 38 %).

Consumption		Low	Middle	High
IRR [%]		30	34	42
LCOE [R$/kWh]		0.17	0.15	0.11
$r = 5$ %	*DP* [years]	4.47	3.81	2.95
	NPV [R$]	66,427.38	136,236.32	293,864.98
$r = 10$ %	*DP* [years]	5.11	4.28	3.25
	NPV [R$]	31,316.39	65,934.09	146,655.66
$r = 15$ %	*DP* [years]	5.99	4.89	3.61
	NPV [R$]	15,405.22	34,070.04	79,919.70
$r = 20$ %	*DP* [years]	7.34	5.75	4.05
	NPV [R$]	7335.75	17,906.94	46,059.74

Table 11
Percentage variation of the viability indicators from the most optimistic to the most pessimistic scenarios from the investor's point of view.

Indicator	Low [%]	Middle [%]	High [%]	Mean [%]
IRR ↓	12.48	12.75	13.21	12.81
LCOE ↑	18.34	18.34	18.34	18.34
DP ↑	93.06	77.74	61.90	77.57
NPV ↓	90.90	89.12	86.96	89.00

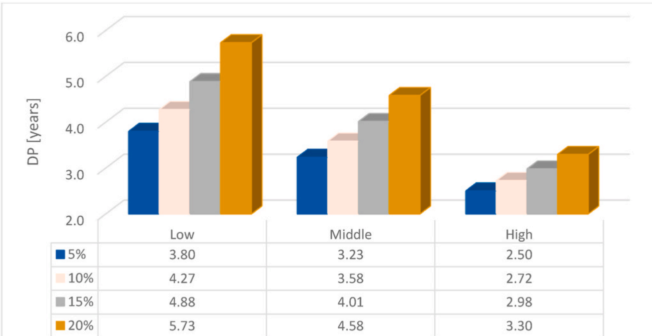

Fig. 4. *DP* for the four rates by consumer unit project (EECS = 100 %).

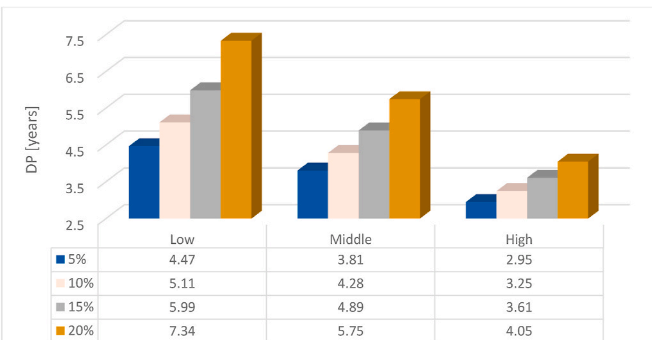

Fig. 5. *DP* for the four rates by consumer unit project (EECS = 38 %).

decrease in *NPV* value of each project, considering the variations in discount rate. Again, it is possible to realize that for the system with greater compensation (EECS = 100 %) the percentage reductions in *NPV* are smaller than for the system with limited compensation (EECS = 38 %). On average, changing the discount rate from 5 % to 10 %, 15 %, and 20 % impacts the *NPV* value by 51.01 %, 74.14 %, and 85.87 %; respectively. As can be observed, the definition of the net-metering policies even affects the sensitivity of the investment in relation to country discount rate.

5.1.2. Net-metering policies (EECS = 100 %, 72 %, and 38 %)

Figs. 8–11 illustrate the impact of the net-metering policies presented by Normative Resolution n° 482/2012, Regulatory Impact Analysis n° 03/2019, and Law n° 14.300/2022 on the *IRR*, *LCOE*, *DP*, and *NPV* of the consumer unit projects (Low, Middle, and High). Comparisons are presented for *r* = 10 %, considering the SELIC at the end of 2023 (11.65 %) and the average of IPCA, IGP-M, and SELIC (7.31 %), as Fig. 2.

From the data in Figs. 8–11, Table 14 presents the percentage variation in *IRR*, *LCOE*, *DP*, and *NPV* of the consumer unit projects, considering EECS = 72 % and EECS = 38 % and adopting EECS = 100 % as a reference. Table 15 shows the average values grouped by EECS. Again, for each viability indicator, the direction of the vertical arrows specifies whether the change corresponds to an increase or decrease in the variable.

According to Tables 14 and 15, in relation to the previous EECS (100 %) the current EECS (72 %) affects the investments, as follows:

- For project Low, *IRR* and *NPV* decrease 5.61 % and 8.93 %, respectively; while *LCOE* and *DP* increase 7.53 % and 8.03 %, respectively.
- For project Middle, *IRR* and *NPV* decrease 5.74 % and 8.57 %, respectively; while *LCOE* and *DP* increase 7.53 % and 7.91 %, respectively.
- For project High, *IRR* and *NPV* decrease 5.96 % and 8.15 %, respectively; while *LCOE* and *DP* increase 7.53 % and 7.79 %, respectively.

Still according to Tables 14 and 15, in relation to the previous EECS (100 %) the considered EECS (38 %) would affect the investments, as follows:

Table 12
Percentage increase in *DP* value for variations in the discount rate from 5 % to 10 %, 15 %, and 20 %.

r [%]	EECS = 100 %			EECS = 38 %			Mean [%]
	Low [%]	Middle [%]	High [%]	Low [%]	Middle [%]	High [%]	
5 → 10	12.47	10.90	8.96	14.42	12.49	10.05	11.55
5 → 15	28.51	24.13	19.13	34.04	28.55	22.29	26.11
5 → 20	50.82	41.69	31.77	64.16	50.93	37.19	46.09

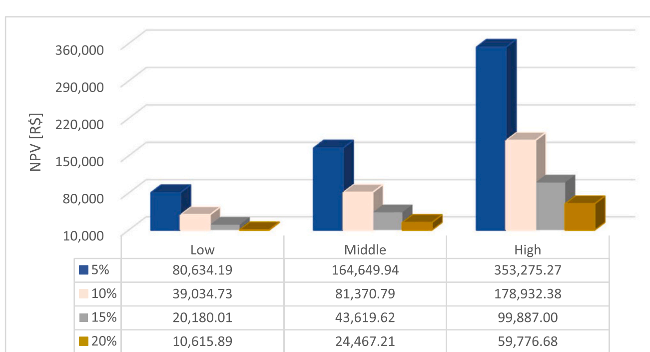

Fig. 6. *NPV* for the four rates by consumer unit project (EECS = 100 %).

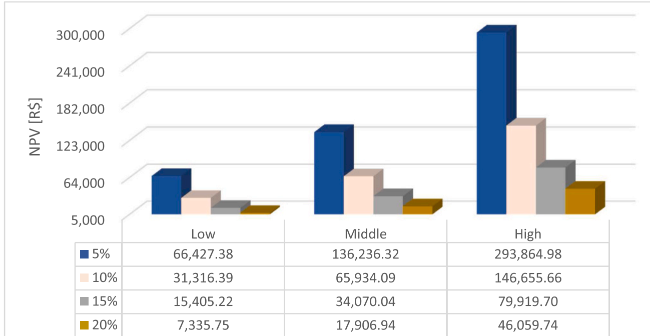

Fig. 7. *NPV* for the four rates by consumer unit project (EECS = 38 %).

Table 13
Percentage decrease in *NPV* value for variations in the discount rate from 5 % to 10 %, 15 %, and 20 %.

r [%]	EECS = 100 %			EECS = 38 %			Mean [%]
	Low [%]	Middle [%]	High [%]	Low [%]	Middle [%]	High [%]	
5 → 10	51.59	50.58	49.35	52.86	51.60	50.09	51.01
5 → 15	74.97	73.51	71.73	76.81	74.99	72.80	74.14
5 → 20	86.83	85.14	83.08	88.96	86.86	84.33	85.87

- For project Low, *IRR* and *NPV* would decrease 12.48 % and 19.77 %, respectively; while *LCOE* and *NPV* would increase 18.34 % and 19.65 %, respectively.
- For project Middle, *IRR* and *NPV* would decrease 12.75 % and 18.97 %, respectively; while *LCOE* and *NPV* would increase 18.34 % and 19.45 %, respectively.
- For project High, *IRR* and *NPV* would decrease 13.21 % and 18.04 %, respectively; while *LCOE* and *NPV* would increase 18.34 % and 19.19 %, respectively.

5.2. Viability indicators across different projects, rates, and compensations

Finally, Table 16 presents the percentage variation of the viability indicators across different energy consumption levels (Low, Middle, and High), discount rates (5 %, 10 %, 15 %, and 20 %), and compensation systems (EECS = 100 %, 72 %, and 38 %). In this analysis, in each scenario, the value of the variables which are not being evaluated is

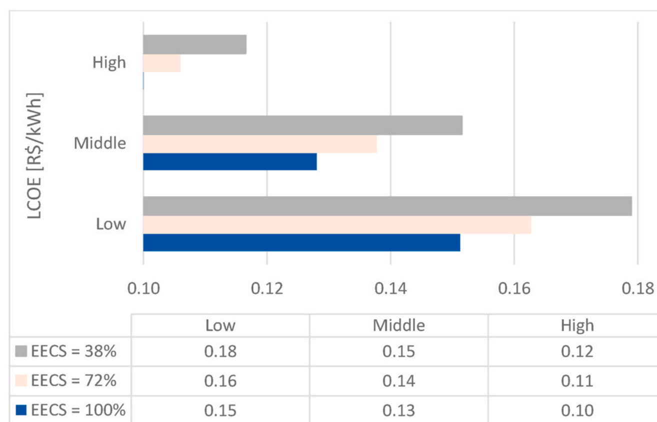

Fig. 9. *LCOE* for net-metering policies by consumer unit project.

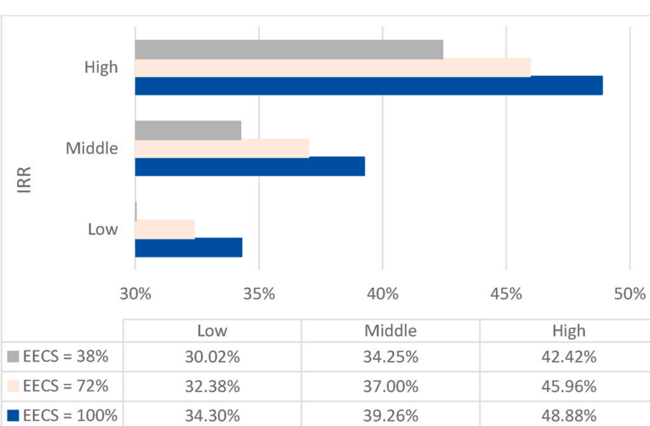

Fig. 8. *IRR* for net-metering policies by consumer unit project.

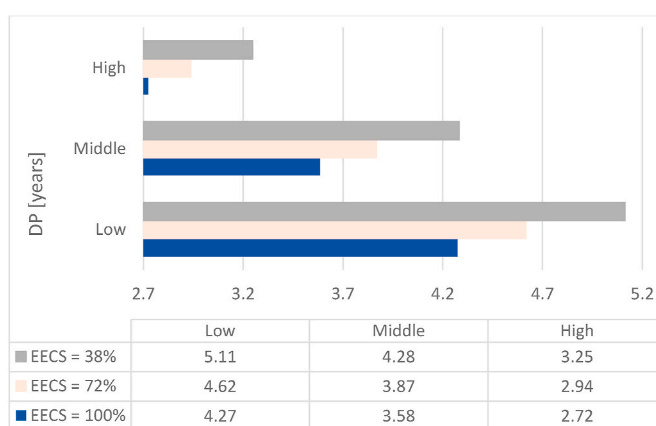

Fig. 10. *DP* for net-metering policies by consumer unit project.

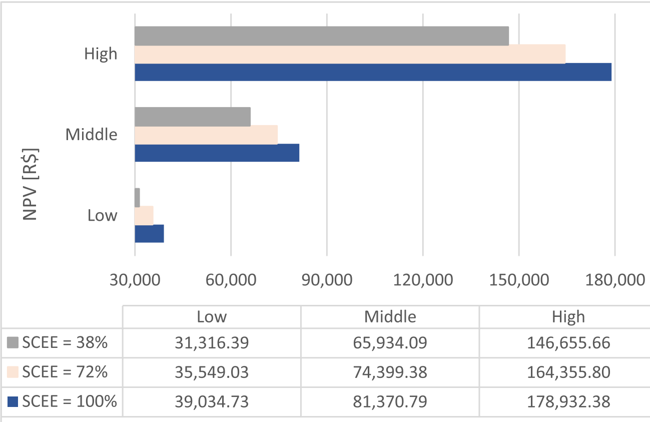

Fig. 11. *NPV* for net-metering policies by consumer unit project.

Table 14
Impact of the net-metering policies for the viability indicators by consumer unit project – individual values.

Indicator [%]	EECS 100 % → 72 %			EECS 100 % → 38 %		
	Low [%]	Middle [%]	High [%]	Low [%]	Middle [%]	High [%]
IRR ↓	5.61	5.74	5.96	12.48	12.75	13.21
LCOE ↑	7.53	7.53	7.53	18.34	18.34	18.34
DP ↑	8.03	7.91	7.79	19.65	19.45	19.19
NPV ↓	8.93	8.57	8.15	19.77	18.97	18.04

Table 15
Impact of the net-metering policies for the viability indicators grouped by EECS – average values.

Indicator [%]	EECS 100 % → 72 %	EECS 100 % → 38 %
IRR ↓	5.77	12.81
LCOE ↑	7.53	18.34
DP ↑	7.91	19.43
NPV ↓	8.55	18.93

defined as the most current or probable (for example, Project = Middle, r = 10 %, and EECS = 72 %). The objective is to evaluate scenarios with a high probability of occurrence and neutralize, as much as possible, the influence of these variables in the analysis.

As justified in Section 5.1, investment profitability increases from Low to High consumption level. Therefore, for analysis across different energy consumption levels, item (a) of Table 16, *IRR* and *NPV* increase and *LCOE* and *DP* decrease from Low to High. It is possible to realize that the percentage variation of all viability indicators is lower for Low→Middle than for Middle→High energy consumption level. From Low→Middle to Middle→High the percentage change in indicators is at least 1.1 times, reaching up to 1.6 times.

Table 16
Percentage variation of the viability indicators across different (a) energy consumption levels, (b) discount rates, and (c) compensation systems.

Scenario		*IRR* [%]	*LCOE* [%]	*DP* [%]	*NPV* [%]
(a)	Level (Low→Middle)	↑ 15.63	↓ 18.75	↓ 16.23	↑ 109.29
	Level (Middle→High)	↑ 24.32	↓ 23.08	↓ 24.03	↑ 120.91
	Difference	*1.6 times*	*1.2 times*	*1.5 times*	*1.1 times*
(b)	r (5 %→ 10 %)	–	–	↑ 11.53	↓ 50.99
	r (10 %→ 15 %)	–	–	↑ 12.92	↓ 47.17
	r (15 %→ 20 %)	–	–	↑ 15.10	↓ 45.29
	Difference on average			*1.1 times*	*1.1 times*
(c)	EECS (100 %→ 72 %)	↓ 5.13	↑ 8.33	↑ 8.10	↓ 8.57
	EECS (72 %→ 38 %)	↓ 8.11	↑ 15.38	↑ 10.59	↓ 11.38
	Difference	*1.6 times*	*1.8 times*	*1.3 times*	*1.3 times*

For analysis across different discount rates, item (b) of Table 16, the percentage variation of indicators is evaluated for each 5 % increase in the discount rate. As justified in Section 5.2, where the r = 5 % is adopted as a reference, *DP* increases and *NPV* decreases as the discount rate rises. The results show that every 5 % increase in the discount rate, the percentage change in indicators is, on average, 1.1 times; ranging from 1.0 to 1.2.

Regarding the analysis across different compensation systems, item (c) of Table 16, the percentage variation of indicators for previous, current, and considered EECS is analyzed. As justified in Section 5.3, where the EECS = 100 % is adopted as a reference, *IRR* and *NPV* decrease and *LCOE* and *DP* increase from 100 % to 38 % compensation system. According to the data, from 100 %→72 to 72 %→38 % the percentage change in indicators is at least 1.3 times, reaching up to 1.8 times.

In summary, the data on Table 16 indicates that the viability of solar PV investments is significantly impacted by the energy consumption level, discount rate adopted, and compensation system in force. Furthermore, when comparing results across projects (Low→Middle→High), r (5 → 10→15 → 20 %), and EECS (100 → 72→38 %), especially the last line of each item on Table 16 (referred as "Difference"), it is noted that for the data considered in this research, the viability indicators are highly influenced by the compensation system, energy consumption level, and discount rate adopted; in this order. That is justified by the highest difference found for the respective items on Table 16 "c" (1.8 times), "a" (1.6 times), and "b" (1.1 times).

6. Key findings, comparison with previous studies, and economic/policy/social implications

Energy transition is a process of worldwide importance that aims to reduce global warming. Among the different ways of contributing to this process, Distributed Generation (DG) using solar Photovoltaic (PV) stands out, especially in Brazil. In order to encourage the growth of this energy source, regulatory mechanisms are adopted, such as net-metering for energy compensation.

Changes in the compensation mechanisms affect the economic viability of solar PV investments and the attractiveness for participants. Therefore, Brazilian Electricity Regulatory Agency (ANEEL) has worked to create a model that keeps the solar sector growing and minimizes the impacts for energy tariff, distribution companies, consumers, prosumers, etc.

Regarding the findings of this research, Section 5.1 showed that technical and cost data of the projects significantly impact the viability of investment. For example, the return for High consumption level in the most pessimistic scenario (Tables 10–42 %) is higher than for the Low consumption level even in the most optimistic scenario (Tables 8–34 %). That is justified by the lower cost/power [R$/Wp] of the High consumption level in relation to Low and Middle consumption levels.

Section 5.2 revealed that the compensation mechanism also affects the sensitivity of the investment in relation to discount rate. The lower the energy compensation, the greater the impact of the discount rate on the viability indicators. For example, the percentage variations in *DP* (Table 12) and *NPV* (Table 13) are smaller for EECS = 100 % than for EECS = 38 %. That is justified by the weight of the energy compensation in the mathematical model developed, Equation (8).

From Section 5.3, it was possible to observe that from the previous (EECS = 100 %) to current (EECS = 72 %) compensation mechanism the return for investor, on average, decreased 5.77 % (Table 15 - left side). However, this reduction would be of 12.81 % if considered (EECS = 38 %) compensation mechanism was adopted (Table 15 - right side).

Finally, Section 5.4 showed that among the three analyzes performed (energy consumption levels, discount rates, and compensation systems) the last one has a greater impact on viability indicators. That can be confirmed by the highest difference found for each item of Table 16.

Concerning the economic implications, lower EECS reduces the investment attractiveness. It is worth emphasizing that the high interest rates charged by Brazilian financing institutions also reduces return on investment and the economic feasibility of solar PV systems. However, for the studies carried out, even in the worst case (Project = Low, $r = 20$ %, and EECS = 38 %) the investment remains viable, with positive *NPV* and *DP* less than 8 years. Therefore, solar PV systems investments are competitive in Brazil.

Positive results for all scenarios were also obtained by Santos & Lucena [23]. In this research, it was concluded that the economic potential is not affected by climate change in all scenarios. Vieira & Carpio [21] also found positive values. Based on the parameters applied in that study, the conclusion shows that the tariff subsidy for grid-connected PV generation is no longer needed in Brazil.

Drumond Jr. et al. [22] concludes that there is a large variation in the results among the Brazilian states and distribution companies. Thus, they affirm that DG from solar PV systems still depend on government incentives to continue increasing adoption in Brazil. Iglesias & Vilaça [14] indicates that appropriated regulation would be between the previous and current EECS. According to that study, the solar PV market growth reduction could directly impact Brazil's commitment to reducing CO_2 emissions, especially in light of the water crisis in which DG can be considered one of the main sources of complementary thermal power plants shares.

In regards to policy/social implications, the previous rule (EECS = 100 %) is the most beneficial for investor's point of view, since the compensation is applied to all components of the residential energy tariff. However, in this case, there is a loss of revenue for the distribution companies, forcing them to charge non-PV owners. In this situation, non-PV owners subsidize grid costs for solar PV owners. According to Iglesias & Vilaça [14], there is a transfer of income from people with adverse financial conditions (non-PV owners) to those in a more favorable financial situation (solar PV owners), which may increase social inequality. As Vieira & Carpio [21], energy security must be ensured by policies that appropriately allocate costs among consumers.

In this context, the current rule (EECS = 72 %) requires the payment of the Distribution Line over the energy consumed, independently of the energy injected into the grid. This alternative mitigates the problems mentioned in the previous paragraph, higher tariffs and social inequality. According to the results of this research, from previous to current rule (EECS = 100 → 72 %) the *DP* and *LCOE* increase around 8 % and the investment remains viable. Therefore, the existing policy, EECS = 72 %, is suitable for the current stage of sector development, minimizing the impacts for energy tariff, distribution companies, consumers, and prosumers.

For EECS = 38 %, it is important to take into account the Paris Agreement. Brazil has committed to reduce greenhouse gas emissions, achieving an estimated 45 % share of renewable energy in the energy matrix [12]. Thus, an extremely restricted compensation mechanism, such as EECS = 38 %, that decreases the solar PV investment attractiveness and leads to a reduction in number of solar PV adopters could difficult accomplishment of the goals set in Paris Agreement. Furthermore, EECS = 38 % can lead loss of jobs created by solar business sector.

Therefore, due to the strong economic, political, and social impact of the changes in the compensation rules, decision makers should follow the expansion of intermittent power sources, especially solar PV, and their impact to the distribution grid by 2029. The objective is to evaluate the consequences of Law n^{o} 14.300/2022 for consumers, companies, and solar business sector. It is important to highlight that the technological evolution of components, batteries, connection of electric vehicles to the grid, and free residential market can lead to further updates to the energy compensation mechanism.

7. Conclusions, limitations, and future works

Although the case studies, results, and policies in this research are specific to Brazilian legislation, the methodology presented can be adapted to any country, even if it employs a different energy compensation mechanism (adaptations might be required depending on tariff regimes). Results and policies depend on the input variables, parameters, assumptions and context of the country; for this reason, they are specific for each case study. Overall, considering all consumer unit projects (Low, Middle, and High), discount rates (5 %, 10 %, 15 %, and 20 %), and EECSs (100 %, 72 %, and 38 %); the viability indicators (*IRR*, *LCOE*, *DP*, and *NPV*) showed high percentage variation between extreme scenarios. Therefore, project characteristics, discount rates, and EECSs significantly affect the analysis of PV investments.

Regarding consumer units (High, Middle, and Low), the results showed that project High is the most profitable, followed by project Middle, and then by project Low. That is justified by the technical and cost data of the considered projects. Project High presents the lowest cost/power ratio [R$/Wp]. It is worth mentioning that the viability indicators for the project High in the most pessimistic scenario (EECS = 38 %) showed better results than for the project Low even in the most optimistic scenario (EECS = 100 %), as long as the same discount rate is adopted. That shows how important the technical and cost characteristics of the projects are in the viability analysis.

In relation to effect of the discount rates (5 %, 10 %, 15 %, and 20 %) on viability indicators, it was possible to realize that percentage increase in *DP* and percentage decrease in *NPV* from the scenarios 5 %→10 %, 5 %→15 %, and 5 %→20 % is smaller for EECS = 100 % than EECS = 38 %. That means, the lower the energy compensation, the greater the impact of the discount rate on the viability analysis. Thus, the definition of the net-metering policies even affects the sensitivity of the investment in relation to country discount rate.

Excluding the influence of the discount rate, that is, setting the rate at 10 %, it was possible to analyze the impact of the net-metering policies on PV investments. For the evaluated case studies and considering as the base scenario REN n^{o} 482/2012 (EECS = 100 %), the approval of Law n^{o} 13.400/2022 (EECS = 72 %), on average, reduces 5.77 % the *IRR* and 8.55 % the *NPV* and increases 7.53 % the *LCOE* and 7.91 % the *DP*. However, if AIR n^{o} 003/2019 (EECS = 38 %) was approved, on average, it would decrease 12.81 % the *IRR* and 18.93 % the *NPV* and it would increase 18.34 % the *LCOE* and 19.43 % the *DP*. *DP* and *NPV* were the indicators most impacted by EECS in percentage terms, followed by *LCOE* and *IRR*.

It is important to highlight that the creation of a legal framework for regulating PV distributed generation contributes to the consolidation of the sector, increasing its predictability and bringing certainty to those involved. In Brazil, after the legal framework in 2012, the PV installed power grew from 8 MW to around 36,000 MW nowadays. The growth in solar energy generation is in line with the Sustainable Development Goals (SDGs), in relation to the use of renewable and clean sources.

In countries with a predominance of hydroelectric generation, like Brazil, energy transition contemplating other renewable sources can bring several additional benefits. In these countries, PV systems, for example, can help reduce: (1) the risks related to not meeting energy demand due to the water crisis, (2) the need to activate thermoelectric plants which increases generation costs in the country, (3) electrical losses in energy transmission and distribution systems, and (4) system overload, especially during peak hours.

As can be seen from the results, restricted compensation (for example, EECS = 38 %) significantly impacts the profitability of the investment, with a reduction in *IRR* of more than 10 %. On the other hand, allowing compensation of all energy injected into the grid (EECS = 100 %), in which the prosumer does not pay for the use of the grid, can harm concessionaires and consumers who have not invested in their own power generation. Thus, a balance when defining the EECS is recommended.

Lastly, it is noteworthy that the 36 evaluated scenarios presented positive results. The worst *DP* (7.34 years) is considered reasonable by most companies. Therefore, even though the net-metering policies in Brazil show a reduction in the percentages of energy compensation from 2023, investments in PV systems remain viable in the country. This contributes to the growth of both distributed generation and solar source. Moreover, it shows reasonableness of the PV regulation adopted in Brazil.

This study has limitations related to uncertainty of future variables. Although all parameters and assumptions have been justified (such as: adjustment rate of the energy tariff, degradation rate of the PV systems, average monthly generation, etc), they can change. In this case, the mathematical model would provide different results. Besides, the mathematical model does not contemplate externalities of the evaluated system, for example the potential for reducing CO_2 emissions, investments in transmission lines, etc.

As future work, two suggestions are presented. The first is to integrate PV systems to electric vehicles. One way to reduce the emission of polluting gases is through replacing combustion vehicles for electric ones. This strategy is interesting when combined with distributed solar PV. Thus, a study on the viability of electric vehicles, including solar PV generation for recharging, could guide decision-makers, regulatory partied and government towards achieving sustainability goals, such as those described in the Sustainable Development Goals (SDGs). The second suggestion is related to subsidies for the solar energy source. In this paper, net-metering rule in Brazil was evaluated. However, around the world several mechanisms are implemented to encourage investment in solar energy projects; such as net-metering, buy-all sell-all, and net-billing. Therefore, a comparison of how different solar PV subsides work and how net-metering rules are applied in other countries would provide a more comprehensive view of the global landscape of solar PV investments.

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CRediT authorship contribution statement

Nathalia Hidalgo Leite: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cindy Paola Guzman Lascano:** Writing – review & editing, Visualization, Validation, Project administration. **Hugo Gabriel Valente Morais:** Writing – review & editing, Validation, Supervision, Project administration. **Luiz Carlos Pereira da Silva:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

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