Branco, José Eduardo Holler; Alves Junior, P. N.; Okamura, Fernando et al.

Article

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International Journal of Energy Economics and Policy

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Branco, José Eduardo Holler/Alves Junior, P. N. et. al. (2024). Examining the impacts of grid tariff on the economic viability of photovoltaic energy : the case of residential power generation in Brazil. In: International Journal of Energy Economics and Policy 14 (5), S. 615 - 628.
https://www.econjournals.com/index.php/ijeep/article/download/16426/8223/39181.
doi:10.32479/ijeep.16426.

IJEEP

INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY

EJ EconJournals

ISSN: 2146-4553

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2024, 14(5), 615-628.

EJ EconJournals

Examining the Impacts of Grid Tariff on the Economic Viability of Photovoltaic Energy: The Case of Residential Power Generation in Brazil

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Received: 16 April 2024 **Accepted:** 22 August 2024 **DOI:** https://doi.org/10.32479/ijeep.16426

ABSTRACT

On-grid photovoltaic systems (PVs) hold immense potential as source of renewable energy, particularly in nations with abundant solar irradiation and large territories. Brazil, in particular, has emerged as a noteworthy example, driving an annual PV capacity installation rate above 150% since 2013. However, the recent Normative Resolution 1.059/2023, stablished by the National Electricity Energy Agency, has introduced grid tariff for utilizing grid infrastructure in Brazil. In light of this, our study aims to assess the impacts of this policy on the economic feasibility of medium-sized residential PVs (rooftops). Our finds demonstrated that the financial indicators for investing in on-grid PVs within medium-sized family homes in Brazil were very attractive prior to 2023, with an average Internal Return Rate (IRR) of 22.7% and a payback of 5.0 years. However, as consequence of the new policy these indicators will deteriorate and reach an average IRR of 15.7% and an average payback of 7.2 years, progressively until 2030. Additionally, it will increase almost 50% the PV electricity levelized cost. We recommend further research directions for policymakers and researchers encompassing several strategies for encouraging again the PV energy in the country, such as promoting joint procurement initiatives, and implementing subsidies for reducing photovoltaic system prices.

Keywords: Solar Energy, Carbon Emission Reduction, Photovoltaic Rooftops, Energy Costs, Energy Policy
JEL Classifications: Q42, Q48, Q41, H2

1. INTRODUCTION

The quest for renewable energy sources stands out as a paramount theme in the 21st century, garnering increased significance amid the escalating challenges of the climate crisis. Among the promising renewable energy options with minimal environmental impact, solar energy emerges as a frontrunner, offering a sustainable and eco-friendly solution to meet the burgeoning energy demand. Photovoltaic systems (PVs) represent cutting-edge technologies that enable the conversion of sunlight into electrical energy, and they have experienced rapid proliferation around the world over the last decade (Dantas and Pompermayer, 2018).

According to IRENA (2016), the technological robustness demonstrated by PVs that have been operating for more than 30 years, the vast technical potential, and the non-emission of greenhouse gases explain this energy alternative's accelerated growth. As per Diamandis (2014), significant strides in solar cell technology have led to a substantial reduction in the cost of PVs. For illustration purposes, the cost of silicon photovoltaic (PV) cells fell from US$79.67 to US$0.36 per watt between 1977 and 2014.

Brazil has played a prominent role in this scenario. The country have a vast territorial area with high solar irradiance levels and potential for PV generation. According to a projection carried out by the Energy Planning Company - EPE (2018), excluding regions not suitable for installing PV systems (e.g., conservation units and legal reserve areas with native vegetation), Brazil has a potential for PV energy generation that can reach 307 Giga Watt peak capacity, with an approximate generation of 506 TWh/year, considering anthropogenic-only areas with solar radiation outstanding at least 6 kWh/m². After 2003, when the Brazilian Federal Government created the "Luz para Todos" ("Light for All") program, aiming to bring electricity to communities living in remote rural areas, the PV technology has spread in Brazil.

In April 2012, the National Electric Energy Agency (ANEEL, 2012) introduced the Normative Resolution Nb. 482/2012[1], providing regulations for distributed energy generation. This resolution established the framework for the compensation system, commonly known internationally as net metering. Under this framework, the energy generated and fed into the grid by a generating unit is transferred to the distributor and offset against the energy consumption of the same generating unit. This net metering system was pivotal in fostering the swift proliferation of PVs throughout Brazil (BNDES, 2018).

Subsequently, according to the Brazilian Solar Energy Association - ABSOLAR (2020), the total installed capacity of PV energy has experienced an impressive average annual growth rate of 150%, doubling each year since 2017. This remarkable surge can be attributed to the PVs' cost-saving benefits to households and businesses. For micro and small businesses, in particular, where electricity bills constitute the second-largest expense after payroll, adopting PVs has proven to be a financially advantageous solution. Additionally, this transition to solar energy contributes significantly to environmental sustainability.

In 2023, more than 300 thousand PVs were installed on the national electricity grid, and the installed capacity of PV systems in Brazil reached 36 GW, constituting a noteworthy 16% of the country's total electrical energy generation capacity.

Despite the notable growth in the PV energy sector, Law Nb. 14,120/21, enacted in 2021, has brought about significant changes. It mandates the cessation of discounts on the grid tariff (named in Brazil as "TUSD-Wire B") for incentivized sources of electrical energy, effective from 2023 onwards. As per the new regulations, PV energy generators injecting electrical energy into the distribution grid will no longer enjoy exemptions from the tariff associated with using energy distributors' infrastructure. Consequently, on-grid PV power generators authorized to generate energy from 2023 must now pay 15% of the TUSD on energy exported to the grid. This tariff will incrementally rise, reaching 100% by 2029.

Due to this new legislation, which removes the subsidy previously given to PV energy generators, systems that are installed from 2023 onwards will have to pay an additional expense, which is the amount charged for the use of the energy network when exporting the surplus energy for the grid. Consequently, this added cost will elevate the overall expense of PV generation, diminishing the financial attractiveness of these systems for investors, and consequently, could become a factor in discouraging the installation of new PV energy units.

1.1. Objective

Therefore, the primary objective of this paper is thorough examination of the implications arising from recent legislation mandating the payment of grid tariff, specifically on the economic viability of medium residential on-grid Photovoltaic (PV) systems in Brazil. Additionally, the paper aims quantifying the consequential escalation in their levelized costs, providing valuable insights for stakeholders in the sector to evaluate the lessening in the competitiveness of PVs in the country resulting from the new policy.

2. BACKGROUND

Cumulative installed solar PV capacity worldwide jumped from 0.10 TW in 2012 to approximately 1.17 TW in 2022 (STATISTA, 2023). According to the International Energy Agency (IEA, 2023), the capacity additions for PV and wind energy are expected to more than double by 2028 compared to 2022. With ongoing policy support, this is attributed to the anticipation that their generation costs will be lower than those for both fossil and non-fossil alternatives in most countries.

2.1. Photovoltaic Systems (PVs) Globally

Available statistics often aggregate all types of PV generation systems. For example, it is known that the global cumulative installed solar PV capacity increased from 138,856 to 1,177,000 MW from 2013 to 2022 - an increase of approximately 850% (STATISTA, 2023). These values evidence an increasing demand for PV energy. It is also known that the regions that most produce PV energy are Asia Pacific (56% of the world's production), Europe (19%), North America (18%), and South and Central America (4%) (OWID, 2023). South and Central Americas and Africa are large continents with high potential but still have low global representation.

The correlation between the increase of the global cumulative installed solar PV capacity and PV self-consumption statistics (both increasing) may indicate that self-consumption represents a significant part of PV generation. Our focus is self-consuming energy generation, considering the final users' perspective.

In this context, PVs can be structured in at least three different system configurations, i.e., in one configuration, the utility infrastructure may be built, operated, and managed by energy companies (in this case, the infrastructure is focused on large-scale demand). In another configuration, the utility infrastructure may be built, operated, and managed by final consumers (i.e., small-scale demand, usually called self-consumption systems or rooftop systems), and a third possible configuration may constitute intermediary solutions with partnerships between energy companies and final consumers. Here, we are investigating a transition from a configuration where final users operated and managed the infrastructure and did not pay for its use to a

1 Resolução Normativa Nº 482, de 17 de abril de 2012.

configuration where final users kept the operation and management but had to pay different rates to use the infrastructure.

An example of a country with multiple system configurations is Finland. (Saikku et al., 2017) investigated the role of private actors through joint procurements for generating PV energy. The authors investigated nine cases, encompassing associations of groups with ten up to 150 people. Seven joint procurements were organized exclusively with private financing. The authors also investigated a case where users could use the distribution infrastructure of Helen, the state electricity company. This was the case when more individuals were interested in entering the energy supply systems.

In Finland, consumers are empowered and find it easier to overcome the high investment expenses thanks to valuable peer support and the opportunity to profit from the favorable reputation of solar electricity. The mainstreaming of joint procurements is one method to create a force that can challenge the current system of energy production and consumption, even while the volumes of solar electricity are currently negligible (Saikku et al., 2017).

While no official policy on solar energy has been formed in Finland, the UK and Germany have actively promoted solar electricity using a feed-in tariff system. However, German consumers pay twice as much for electricity as they do in Finland. As a result, Germany's solar PV payback period is now half as long as Finland's (EUROSTAT, 2015).

Considering the perspectives of other countries, there is still a lack of data and academic research on the theme, especially in developing economies, where the increasing potential is huge. The installed PV capacity in 2022 of China was 393 GW, India, 63 GW, Brazil, 24 GW, Spain, 21 GW, Mexico, 9 GW, and Chile, 6 GW (OWID, 2023). Investigating policies for PV generation in developing countries such as Brazil is an urgent need and particularly useful because the findings can be applied in other contexts, such as those in the African continent.

Thackur and Chakraborty (2019) investigated the compensating mechanisms for promoting PV energy generation in India. The authors assumed that it is critical to adopt compensating mechanisms and policies to make the country achieve the national solar energy targets. They investigated five different compensation mechanisms. None of the five analyzed cases charges the users for generating or distributing electricity. The authors concluded that the customer's savings depended on the solar panel size and the compensating mechanisms. Depending on the cases, the payback varied from 7 to 12 years.

Therefore, Thackur and Chakraborty (2019) concluded it is crucial for any country's net metering legislation to be inclusive and capable of addressing the viability of various customer categories. Shared renewable energy sources or shared net metering (i.e., joint procurement) provides a net metering policy design alternative that can lessen the drawbacks of the traditional net metering process. Community involvement fostered by shared net metering solutions results in access to sustainable energy.

Xue et al. (2024) investigated the economic viability of urban rooftops in a higher urbanized region of China. The authors concluded that higher urbanization levels, electricity tariffs, and PV self-consumption rates generally result in a better performance for PV rooftops regarding economic scale and profitability.

2.2. PVs in Brazil: Models and Legislation

Rigo et al. (2019) made a systematic literature review and discussed six fundamental viewpoints and 43 critical success factors for small-scale PV solar energy growth in Brazil. The most cited fundamental viewpoints were economic, followed by political, technological, and then the last three were environmental, social, and marketing. The most cited critical success factors were the price of energy charge, system cost, energy bill reduction, government incentives and policies, and grid connection. Although PV solar energy has a high potential for growth in Brazil, it faces several barriers that need to be overcome. Some actions could improve the situation, such as reducing taxes and tariffs, increasing financing options, simplifying regulations and procedures, promoting education and awareness, and fostering innovation and research.

Pires et al. (2023) proposed a multi-objective optimization method using Response Surface Methodology to evaluate the environmental and financial impacts (carbon footprint and net present value) of different combinations of renewable sources (wind and PV hybrid generation) and types of battery energy storage, considering a tariff policy issue for the on-grid residential scenario in Brazil. The authors found lithium-ion batteries were more suitable than lead-acid batteries for energy storage. Batteries can contribute to the quality of the grid. Still, using batteries for later use at peak hours was not advantageous, and only regions with favorable environmental conditions and higher energy tariffs became financially viable for their proposed model.

According to Pires et al. (2023), Brazilian legislation has recently introduced new rules for distributed generation and net metering. These laws aim to balance the interests of consumers, distributors, and generators. The net-metering scheme allows consumers to generate their electricity and use credits to reduce their bills within a maximum interval of 60 months. However, it does not have a specific regulatory framework for energy storage technologies, which penalizes the investment in this type of technology.

De Faria et al. (2017) reviewed the development, challenges, and prospects of distributed generation with on-grid PVs in Brazil and suggested policy recommendations to promote solar energy. PV generation is an important alternative for diversifying the electric energy matrix in Brazil, reducing greenhouse gas emissions, enhancing energy security, and fostering social and economic development, but the authors found out that despite the high potential for solar energy utilization in Brazil, it faces several barriers such as high costs, lack of incentives, low awareness, and technical and institutional limitations. The existing support mechanisms are insufficient to stimulate the widespread adoption of PV systems, especially in the distributed generation segment.

De Faria et al. (2017) suggested that future research to evaluate the impacts of PV generation on the power system operation and planning, to assess the social and environmental benefits of solar energy projects, to design optimal tariff structures and compensation schemes for distributed generation, and to explore the potential of hybrid systems and smart grids for enhancing PV performance.

Xavier et al. (2015) simulated and analyzed the operation and economic feasibility of microgrids with PV generation and energy storage in Brazil, considering different topologies and scenarios, allowing residential consumers to trade surplus energy among themselves or sell it to the utility. The authors generated data for solar radiation, estimated the size of the PV systems and batteries, calculated the energy balance and power flow, and performed economic and sensitivity analyses. They found out that microgrids can improve the economic feasibility of PV systems, but it was still not viable with current prices and regulations (from 2015). The authors concluded that microgrids may be an alternative to diversifying energy sources and increasing reliability. Still, they require more incentives and regulations to become feasible in Brazil, such as cost reduction of PV modules, the adoption of time-of-use tariffs, and labeling buildings.

Valadão et al. (2023) compared the economic viability of on-grid PV systems and conventional grid electricity for agricultural irrigation in Brazil before and after implementing a decree that eliminated discounts for rural consumers in 2018. The authors conducted a life cycle cost analysis for both systems, considering different scenarios of Brazil's electricity demand, PV generation, and tax rates of five geographic regions. They used historical data on electricity tariffs and solar irradiation to model the costs and benefits of each system over 25 years.

Valadão et al. (2023) showed that the PV system had a lower life cycle cost than the conventional grid system in all regions after the decree, especially in the Center-Western region, where the economy is based on agriculture. The viability of the PV system depended on the annual electricity demand, the solar irradiation level, and the tax on the circulation of goods and services (ICMS) rate. The PV system also demonstrated resilience to regulatory changes, as its cost increased by only 12%, compared to 42% for the conventional grid system, highlighting the potential of PV systems as a sustainable and cost-effective alternative for irrigation in the context of changes in tariff legislation.

Valadão et al. (2023) stated the following points about the Brazilian legislation: The discounts on electricity tariffs for rural consumers who used irrigation or aquaculture at specific times were reduced and phased out by a decree in 2018, which increased the electricity costs for irrigators by over 40%; Two normative resolutions from 2012 and 2015 regulated the installed power, the credit consumption period, and the tax exemptions for distributed microgeneration and net metering, allowing consumers to generate their energy using renewable sources and connect to the power network.

2.3. PVs Economic Evaluations

Many studies have evaluated the economic viability of PV energy in different countries, demonstrating that this technology has proven to be economically attractive, in addition to the environmental benefits it promotes.

Lang et al. (2016) studied the economic viability of home PVs in Germany, Switzerland, and Austria, finding attractive results, with an average internal return rate (IRR) of 4.9% for small homes and 13.4% for large homes. A forecast of PV-levelized costs in the UK until 2035 for various system sizes revealed costs ranging from $ 51/MWh to $ 149/MWh. Notably, these costs are already lower than the prevailing market electricity price (Mandys et al., 2023). García-López et al. (2023) calculated the levelized cost of household PV energy in Spain, finding values between EU$ 0.15-0.21/Kwh, lower than the current prices paid by consumers to energy companies, which present values between EU$ 0.28-0.29/Kwh. Jurasz and Campana (2019) found that PV can cut office buildings' electricity costs in Poland by 1.2% and up to 5.8%.

Analyzing the economic viability of PVs in the UAE, Abo-Khalil et al. (2023) found an average payback of 3.5 years to recover the investments made in a system with a power of 260W. Sinaga et al. (2019) assessed the levelized cost of on-grid PV energy in Indonesia, and the economic modeling found costs at the level of US$0.19-0.21/kWh. Thakur and Chakraborty (2019) found a payback from 7 to 12 years for PVs in India, depending on the size of the panel and the compensating mechanisms. Xue et al. (2024) divided the analyzed Chinese highly-urbanized city sample into two groups of buildings: (i) commercial and industrial (C&I) and (ii) residential (R). The IRR was 14.6-19.2% for "C&I" and 9.9-15.9% for "R." However, the worst-performing cities reached 4.9% and 4.4%, respectively. The payback in the worst-performing cities was 3.4 years for "R" and 5.8 years for "C&I."

Economic feasibility analysis on PV energy carried out by Espinoza et al. (2019) in three large cities in Peru calculated the levelized cost of electricity, finding values between US$ 0.10-0.20/KWh. These costs turned out to be 4% to 38% lower than the final electricity tariffs charged to consumers by energy companies.

Rodrigues et al. (2016) conducted economic viability analyses of small-scale PV systems in thirteen countries, including Brazil. The results found financial indicators such as the IRR varying between 2 and 17% and payback with values between 8 and 25 years. Nijsse et al. (2023) calculated and projected the levelized cost of various energy sources until 2040 for different regions worldwide. The findings suggested that, in Brazil, PV energy costs between 2023 and 2040 will be the most economical, with values falling below $ 50/MWh.

Dantas and Pompermayer (2018) calculated the levelized costs of residential PV generation in different Brazilian regions and compared them with the prices of energy tariffs paid by consumers in each location. They found that approximately 36% of Brazilian cities had a cost ratio for PV energy generation and the price of energy expended for consumption in homes between 50% and 60%, 37% of cities with a ratio between 60% and 70%, 21% of cities with a ratio between 70% and 80% and 5% of them with a relationship between 80% and 90%. In other words, more than 90% of Brazilian cities demonstrated a PV generation cost at least

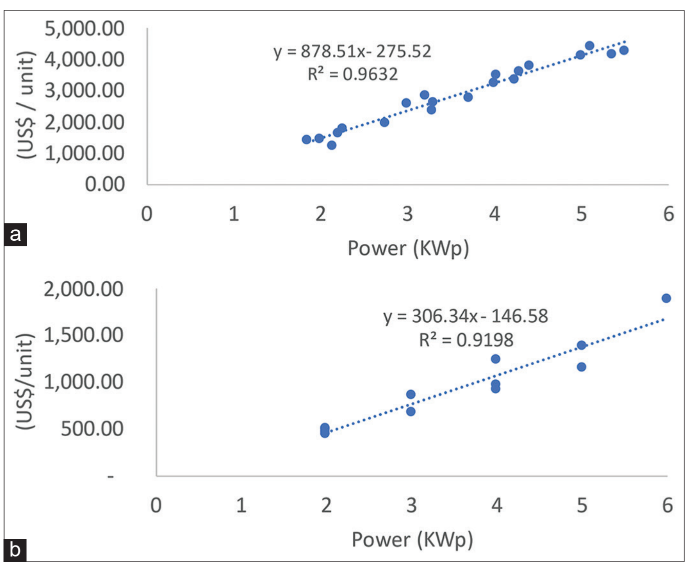
20% lower than the energy tariff paid by consumers to electricity companies.

Over the expansive phase of PV power in Brazil, numerous authors have conducted scientific analyses on the economic feasibility of implementing solar rooftop on-grid systems considering different capacities (Casarin, 2019; Rigo et al., 2019; Siqueira, 2017; Souza and Penha, 2020; Correa, 2020; Moreira et al., 2018; Gomes et al., 2020; Mendes da Silva and Carneiro, 2022). Table 1 summarizes the economic feasibility analysis performed by these authors.

Notably, these studies computed a discounted payback period spanning from 5.8 to 8.1 years to recover the capital investment. The median of the reported payback times stands at 6.5 years. This outcome serves as a benchmark for understanding the time required to recoup capital investments in rooftop on-grid systems in Brazil over the past 5 years.

While the IRR was not consistently provided in all studies, the reported IRR varied between 22.7% and 30.0%. These figures underscore the highly attractive returns on investments in such projects. Despite the existing body of research on the economic viability of PV energy in Brazil, this study uniquely contributes by providing updated analyses after the enactment of new legislation mandating grid tariff payment for using the energy distribution system. It aims to assess the impact of these recent regulations on the economic attractiveness of forthcoming PV projects.

Figure 1: Commercial prices of photovoltaic equipment (a) and inverter prices (b) versus power (KWp)



3. MATERIALS AND METHODS

3.1. Estimation of Free Cash Flow Gains (Inflows)

To evaluate the economic viability of PV energy generation, initially, we estimated the free cash flow, which represents the costs and benefits associated with on-grid PVs.

The gains provided by the PVs correspond to the savings achieved by system owners through a reduction in their electricity bills. The calculation of these gains involves converting the amount of energy generated by the system into monetary values (as given by Equation 1). This approach allows for a comprehensive assessment of the financial impact and cost-effectiveness of installing and operating on-grid PVs.

$$CI_p^r = \frac{E_p^r * ER^r}{(1 - IT^r\,\%)} \quad (1)$$

Where: CI_p^r: cash inflow (gains) in period p at region r; E_p^r: energy produced by the PV system in period p at region r; ER^r: energy price rate charged by the energy distribution company at region r; $IT\%$: indirect taxes charged over the final energy price, at each region r.

The amount of energy generated by the PVs is influenced by factors such as the solar irradiance specific to each geographical region, the power rating of the equipment, and the number of solar panels. For our analysis, we have chosen standard residential PVs commonly installed in homes with three to four residents. According to PORTAL SOLAR (2023), the most prevalent choice for residential installations in Brazil within this category has a power rating of approximately 2.67 kilowatts peak (KWp).

The total energy generated by the PVs is determined by the peak power output of the solar panels, solar irradiance, and the system's efficiency in converting solar energy into electrical energy, as expressed by Equation 2.

Table 1: Summary of economic feasibility analysis of PV rooftop on-grid systems

Region/State[1]	KWp[2]	OL[3] (years)	MRA4 (%)	CAPEX[5] (US$)	IRR[6] (%)	Payback[7]	Author[8]
SC	5.1	20.0		$ 5,175.98	22.7	8.2	[1]
BR	4.0	25.0	2.5	$ 4,331.26	25.4	5.8	[2]
MG	13.8	15.0	7.4	$ 13,871.64		7.0	[3]
RN	11.9	25.0	5.0	$ 10,612.84	30.0	5.0	[4]
RS	2.3	25.0	1.4	$ 2,521.74		8.1	[5]
RS	7.0	25.0	1.4	$ 7,546.58		8.1	[5]
BR	2.1	25.0		$ 4,068.99		6.0	[6]
PB	2.1	25.0	11.8	$ 2,070.39	26.0	5.0	[7]

[1]Region/State: SC (Santa Catarina), BR (Brazil), MG (Minas Gerais), RN (Rio Grande do Norte), RS Rio Grande do Sul), PB (Paraíba). [2]KWp: Capacity in Kilowatt Peak (KWp). [3]OL: Operating life. [4]MRA: Minimum rate of attractively per year (%). [5]CAPEX: Capital Expenditure - US$ (costs of PV system installation). Exchange rate (U$/R$) used for converting CAPEX was U$ 4,83/R$ (BACEN, 2023). 6IRR: Internal Return Rate (%). [7]Payback: Discounted payback considering the MRA (years). [8][1] Casarin (2019),[2] Rigo et al. (2019),[3] Siqueira (2017),[4] Souza and Penha (2020),[5] Correa (2020),[6] Moreira et al. (2018),[7] Mendes da Silva and Carneiro (2022)

$$E_p^r = P * \frac{SI^r}{I_{stc}} * CF \quad (2)$$

Where: E_p^r: energy produced by the PV system in period p at region r; P: peak power of PV system (Kwp); SI^r: average solar irradiance at region r (Kw/m²); I_{stc}: irradiance at standard test condition (1 Kw/m²); and CF: solar energy conversion factor into electrical energy by the PV system (%).

The irradiance within each region (represented as SI^r) was computed as the mean of the annual irradiation of the locations in each state, utilizing the incident solar radiation database from CRESESB (2023). The average solar irradiance of each state (UF) considered in the study is presented in Table A-1 in Appendix I.

The chosen solar-to-electric energy conversion factor for our calculation was 80%, a value well within the established range of conversion capacities documented in various studies concerning the efficiency of electrical energy generation in Brazil (PORTAL SOLAR, 2023b; Casarin, 2019; Rigo et al., 2019; Siqueira, 2017; Souza and Penha, 2020; Correa, 2020; Moreira et al., 2018; Gomes et al., 2020; Mendes da Silva and Carneiro, 2022). Based on these studies, we considered a reduction rate in electrical energy generation power of 0.75% per year, caused by the loss of solar energy absorption capacity over the useful life of the equipment.

The price of the electricity tariff in each region (represented by ER^r) corresponds to the value charged to residential consumers by the energy distributor company operating in the capital. These tariffs encompass the costs of acquisition, transmission, and distribution of energy and are published in the energy supply contracts in force in 2023, authorized by the National Electric Energy Agency (ANEEL, 2023a). The average electric energy price for each UF used in the analysis is in Table A-1 in APPENDIX I.

3.2. Estimation of Free Cash Flow Costs (Outflows)

Cash outflows correspond to investments made in the purchase and installation of the PVs, maintenance costs, replacement costs for the electric current inverter, and estimated costs with the payment for using the electrical distribution infrastructure (grid tariff), as expressed in Equation 3. The grid tariff began to be charged in 2003, as determined by the Normative Resolution ANEEL N° 1.059/2023, published by the National Electric Energy Agency (ANEEL, 2023b).

$$CO_p^r = IPS_p + MC_p + IINV_p + CUN_p^r \quad (3)$$

Where: CO_p^r: cash outflow in period p at region r; IPS_p: investment on PV system in period p; MC_p: maintenance cost of solar cells in period p; $IINV_p$: investment on inverter in period p; and CUN_p^r: cost of the energy company network (grid) utilization in period p at region r.

We calculated the investment cost in the PVs (represented by IPS_p) based on the average prices of equipment sold online in 2023 in the country, using a sample of twenty equipment sets (prices quoted include solar panels, inverter, wiring, and mounting structures). We applied a linear regression analysis to calculate Equation 4., which relates equipment prices to their power output.

Similarly, the investment cost was determined exclusively for inverters (represented by $IINV_p$), utilizing a sample of 12 prices quoted, resulting in Equation 5. Figure 1 visually represent the relationship between PVs' commercial prices and power and the linear regression curves.

The robustness of the regressions is evident in the high adjusted R^2 values, indicating a strong correlation between equipment prices and power. Additionally, the p-value for both regressions was found to be <0.01%, providing statistical significance and allowing us to reject the null hypothesis (H0) that there is no relationship between the prices of PVs and their powers. This statistical rigor reinforces the reliability of our regression analyses.

$$PS = 878.51 * p - 275.52 \quad (4)$$

$$IN = 306.34 * p - 146.58 \quad (5)$$

Where: PS: PVs price (US$); IN: inverter price (US$); p: power (KWp).

Utilizing Equation 4 to estimate the cost of the photovoltaic system, considering the reference power selected for the economic feasibility analysis in this study (2.67 KWp) yields an investment value of US$ 2,070.10. To this amount, the installation cost of US$ 890.30, reported by (PORTAL SOLAR, 2023c), is added, resulting in a total investment of US$ 2,960.40.

Using Equation 5, the investment cost only in the inverter is calculated at US$ 671.33.

We adopted a useful life period of 20 years for the solar panels and 10 years for the inverters, based on the average warranty periods provided by equipment producers, as determined from the sample pricing conducted as part of this study.

The value of US$ 66.25/year is adopted as maintenance cost (represented as MC_p), based on a study presented by PORTAL SOLAR (2023a).

The calculation of the cost of using the distribution network (represented as CUN_p^r) is done using Equation 6:

$$CUN_p^r = \frac{EE_p^r * GT_p^r}{(1 - IT^r\%)} \quad (6)$$

Where: CUN_p^r: cost of the energy company network (grid) utilization in period p at region r; EE_p^r: exported energy to the energy company network (grid) in period p at region r; GT_p^r: grid tariff charged for utilization of electric network (grid) in period p at region r; and $IT\%$: indirect taxes charged over the final energy price, at each region r.

The energy exported to the electric grid (EE_p^r) is determined by subtracting the energy directly consumed by the residence during daylight hours from the total energy generated by the PVs, as expressed in Equation 7:

$$EE_p^r = E_p^r * FEXP \tag{7}$$

Where: EE_p^r : exported energy to energy company network (grid) in period p at region r; E_p^r : energy produced by the PVs in period p at region r; $FEXP$: fraction of the energy exported to the energy company network (grid).

Table 2 provides a detailed overview of energy consumption for a typical middle-class Brazilian family, segmented by various types of energy usage. For each category, the following assumptions were made:

i. The portion of energy consumption that occurs during daylight hours represents direct utilization from the PVs' electricity production.
ii. The surplus of energy produced will be exported to the grid and subsequently, this surplus will be imported and consumed by the residence from the distribution company during periods when the PV equipment is inactive (without sunlight).

Based on this consumption distribution, it was estimated that approximately 24.77% of the energy generated by the system would be consumed directly, while the fraction of energy exported to the energy company network (*FEXP*) would account for the remaining 75.23%.

The grid tariff is the value charged for the utilization of the electric grid in period at region (represented as GT_p^r), and it corresponds to the grid tariff charged by energy distributors in the respective capitals of the Brazilian states, published by (ANEEL, 2023a). The grid tariff is a parcel of the distribution system usage tariff (TUSD) defined as TUSD-Wire B which is charged for using the infrastructure of the utility's distribution network.

Table A-1 of Appendix A presents the grid tariff (TUSD-Wire B) of each state considered in the study.

The fraction of this tariff each year that will apply to energy exported to the grid, starting from 2023, has been specified in ANEEL Normative Resolution N° 1059/2023. This resolution outlines the obligatory grid tariff payment schedule, with progressively increasing percentages, as detailed in Table 3.

Utilizing the methods and data elucidated earlier, we have calculated the cash flow inflows and outflows for an investment project in PVs in each state.

The financial indicators commonly used for project economic evaluations, including the IRR, Net Present Value (*NPV*), and the discounted payback period (DPP), were calculated based on the projected free cash flows.

As indirect taxes, the value-added tax that will be levied on electrical energy services in the coming years was considered, which is 25%. This tax will be charged in accordance with new tax legislation that is being approved by the Federal Government and which will replace the old taxes that were levied on energy services (ICMS, PIS and COFINS).

The levelized cost (CE^r) of electricity generation from the PVs was computed by aggregating the present value of all projected cash outflows over 20 years. This total value was subsequently divided by the amount of energy generated during the same period, as outlined in Equation 8.

$$CE^r = \frac{\sum_{p=1}^{20} \frac{CO_p^r}{(1+i\%)^p}}{\sum_{p=1}^{20} E_p^r}, \forall r \tag{8}$$

Where: CE: cost of PV energy at region r; CO_p^r : cash outflow in period p at region r; E_p^r : energy produced by the PVs in period p at region r; and $i\%$: discount rate.

Aiming at evaluating the impact of the new ANEEL regulation mandating the payment of grid tariff, we defined four scenarios for the analysis:

Table 2: Break down of electricity consumption by usage category, fraction consumed during day and the fraction exported to grid

Energy consumption by use (A) (%)		Day light consumption (B) (%)	Direct Consumption by use[1] (C=A × B) (%)	Energy exported to grid[2] (A-C) (%)
Air conditioning	31.30	0.00	0.00	31.30
Lighting	4.50	0.00	0.00	4.50
Washing clothes	2.50	100.00	2.50	0.00
Food refrigeration	28.30	33.33	9.43	18.87
Entertainment	5.60	33.33	1.87	3.73
Other electronics	9.00	33.33	3.00	6.00
Water heating	12.50	33.33	4.17	8.33
Cooking food	4.70	66.67	3.13	1.57
Personal beauty	0.80	0.00	0.00	0.80
Cleaning	0.40	100.00	0.40	0.00
Food preparation	0.40	66.67	0.27	0.13
Total	100.00		24.77	75.23

[1]Fraction of the energy supplied by the photovoltaic system during the day (sun light period) consumed directly by the house. [2]Fraction of the exceeding energy supplied by the photovoltaic system during the day (sun light period) exported to the grid and imported and consumed after in the time without sun light
Source: EPE (2023)

i. Scenario before 2023 (Bef-23): Envisages the installation of the PVs and the initiation of energy export before 2023, preceding the implementation of the new ANEEL regulation that mandates the payment of grid tariff. This scenario does not account for the payment of grid energy utilization.
ii. 2023 Scenario (23S): Envisages the installation of the PVs and the initiation of energy export starting in 2023.
iii. 2025 Scenario (25S): Envisages the installation of the PVs and the initiation of energy export starting in 2025.
iv. 2030 Scenario (30S): Assumes the installation of the PVs and energy export starting in 2030.

4. RESULTS AND DISCUSSIONS

The discounted payback period (DPP) is a commonly used metric in deciding to invest in PVs. It represents the time required for the sum of economic gains provided by the system over its useful life (calculated in present value terms) to be sufficient to recover the investment made in the equipment purchase and installation. The distribution of calculated DPPs is illustrated in II. Detailed results for each state are presented in Table A-2 within Appendix A.

The DPP distribution of Bef-23 shows a first quartile of 4.5 years and a third quartile of 6.0 years. In the 23S, the first quartile is 5.3 years, and the third quartile is 7.6 years. The 25S sees an increase in the first quartile to 6.4 years and the third quartile to 8.6 years. The 30S extends the first quartile to 6.8 years and the third quartile to 9.0 years.

Comparing the four investigated scenarios the average payback time from the Bef-23 scenario was 5.0, from the 23S was 5.9 years (+17%), from the 25S was 6.5 years (+30%), and from the 30S was 7.2 years (+43% in comparison to Bef-23 scenario).

Globally, DPPs from 8 to 25 years have been observed in a sample of developing and developed countries Rodrigues et al. (2016). Previously investigations in Brazil (i.e., before the grid tariff have registered DPPs from 5 to 8.2 years (Table 1), what suggest that the Bef-23 results are congruent with the reality (4.5-6.0).

The observed extended DPPs in each scenario reflect the impact of the new Normative Resolution ANEEL N°1.059/2023 on the economics of PVs (Figure 2). Prior to the mandatory grid tariff, which formerly served as a subsidy for PV energy generation, the economic benefits provided by the system were considerably more substantial. This allowed investors to recoup their investments rapidly, with an average payback period of approximately 5.0 years (a quarter of the equipment's useful life). Therefore, installing PVs was highly attractive from an economic standpoint, contributing significantly to the rapid expansion of solar energy in Brazil.

Comparing our results to other results in developing countries, Xue et al. (2024) observed a DPP of 3.4 years for residential purposes and 5.8 years for commercial and industrial purposes in Chinese highly urbanized cities. Unlike the Chinese context, our investigation encompassed residential use in rural and low-urbanized areas.

Table 3: Fraction of grid tariff (TUSD-Wire B) payment determined by ANEEL Normative Resolution Nº 1,059/2023

Year	2023	2024	2025	2026	2027	2028	2029 (and after)
% of grid tariff	15	30	45	60	75	90	100

Source: ANEEL Normative Resolution N° 1,059/2023

Figure 2: Distribution of paybacks for investment made in photovoltaic systems

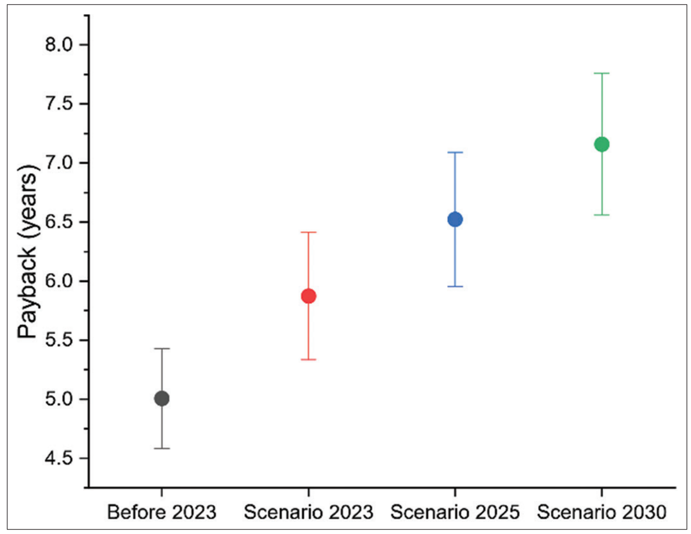
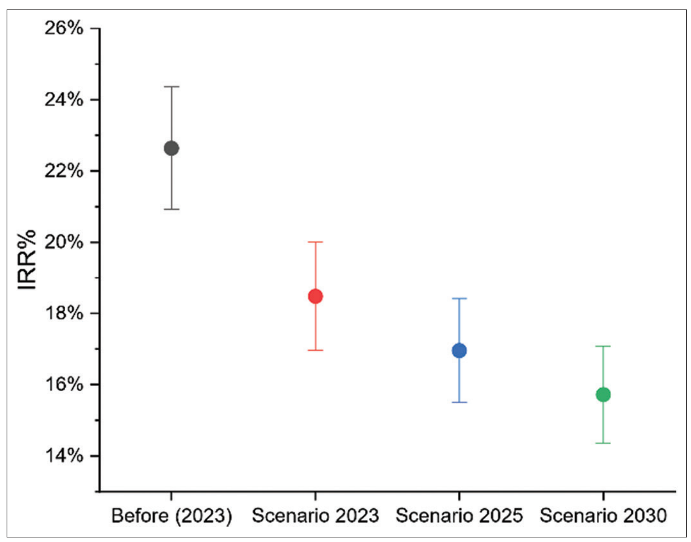


Figure 3: Distribution of internal return rate of investment made in photovoltaic systems calculated for the national average



Introducing the grid tariff in Brazil impacted the economic return, extending the average DPP from 5.0 to 5.9 years. With the gradual increase in this tariff requirement, starting at 15% in 2023 and reaching 100% in 2029, the economic consequences for those investing in PVs from 2023 onwards remain relatively moderate. However, for those who commence PV energy production from 2025 onwards, it will take roughly 6.5 years to recover the investment, and the DPP would be roughly 7.2 years for those starting production from 2030.

For comparative purpose, Thakur and Chakraborty (2019) calculated DPP ranging between 5 and 12 years in India. The authors analyzed five compensating mechanisms, and none charged the final users for generating and distributing electricity. Differently from our investigation, which assumed a standard solar panel size, the authors explored the possibility of building different sizes of solar panels. Therefore, we can argue that the results of 23S, 25S, and 30S are included in the range of DPPs observed in India.

However, it is worth noting that the highest DPP (11 years) in Brazil from 30S is still lower than in India (12 years) (Thakur and Chakraborty, 2019). Similarly, the 30S presented a result comparable to developed countries such as Finland (11 years) (Saikku et al., 2017). It is interesting to highlight that Sakku et al. (2017) investigated a spontaneous joint procurement context (without any policy to promote it), and Thakur and Chakraborty (2019) suggested that policies for promoting joint procurements should be created, given the high DPP.

The reduced economic returns resulting from additional expenses caused by the grid tariff can also be assessed through IRR on investments in PVs. The average IRR observed in the states in the Bef-2023 was 22.68%. However, in the 23S, this rate decreased to 18.37%, further reducing to 17.00% in the 25S and eventually to 15.70% in the 30S (Figure 3). The found results are compatible with the global scope (2 and 17%) Rodrigues et al. (2016).

The 30S result is near to IRR of large houses PVs in Germany, Switzerland, and Austria (13.4%) (Lang et al., 2016) and PVs in highly urbanized Chinese cities (Xue et al., 2024).

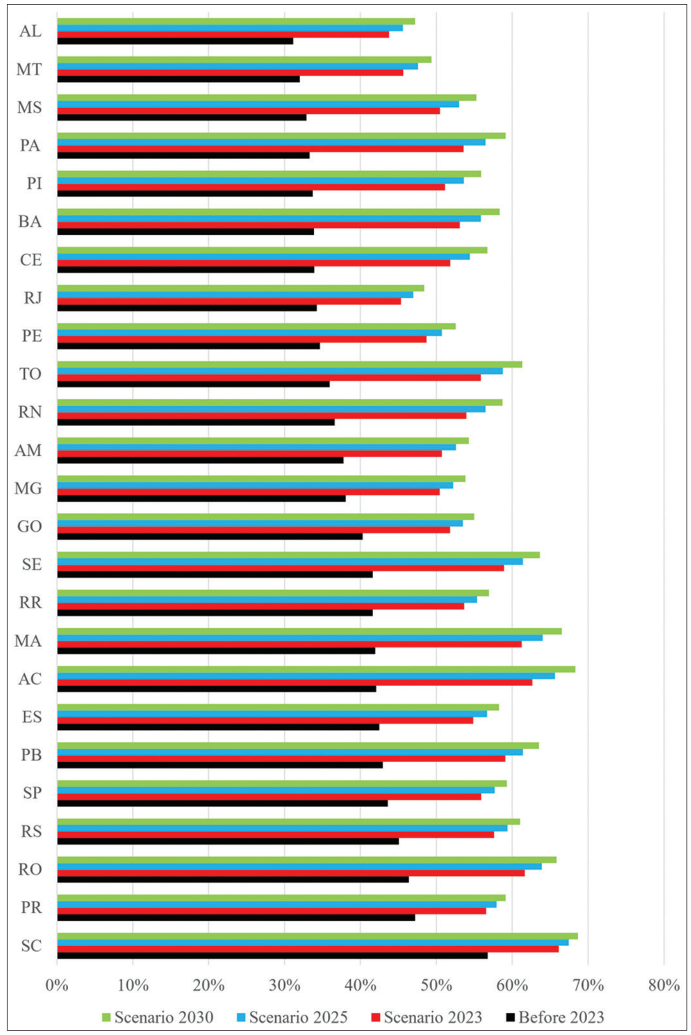
Once again, it is evident that prior to the regulation, the economic return provided by PV energy generation was attractive enough to justify the large numbers of new investments on PVs. However, as the system is installed further along 2023, the IRR diminishes, as indicated by the distribution of IRRs calculated in each scenario for the country's states, as illustrated in the accompanying III. Table A-2 of Appendix A shows the specific IRR calculated for each state.

Analyzing the levelized cost, Figure 4 presents the relative cost of PV energy (the relationship between the levelized cost of PV energy generated in each state and the price of electrical energy sold by energy distributors in each state). It is clearly observed that the levelized cost calculated for each state are heterogeneous. This variation can be explained due to differences on solar irradiation, on grid tariffs, and on energy prices.

The relative cost of PV energy in relation to the cost of energy sold by the electricity distributor prior to the new regulation ranged from 31% (in the most competitive state) to 57% (in the least competitive state). Post-implementation of grid tariff, the relative costs expanded to a range between 47% (in the most competitive state) and 69% (in the least competitive state).

It is worth noting that according to the results, the state of Alagoas (AL) presents the lowest relative cost, meaning it's the state where PV energy cost is most competitive regarding energy prices. In

Figure 4: Relative cost of photovoltaic systems energy in each state in relation to the cost of energy sold by the electricity distributor

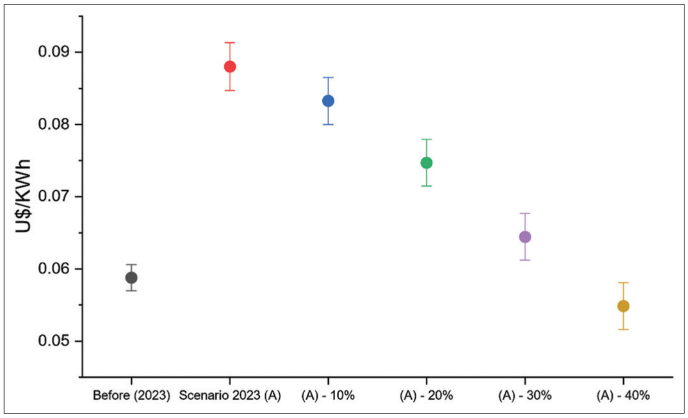


this state, the cost of energy in the Bef-2023 corresponds to 31% of the price of electricity sold by the energy company. In the 23S, the relative cost rises to 44%, and in the 25S, to 46%, reaching 47% in the 2030S. The state that presented the highest relative cost was Santa Catarina (SC), where the cost increased from 57% in the 23S to 69% in the 30S. Table A-3 of Appendix A presents the relative costs calculated for each state. It is worth noting that AL is a Northeastern state, and SC is a Southern state; the distance between the capitals of both states is 3,135 km. Thus, their realities may be different and reflected in the variations of solar irradiation.

As a consequence of the grid tariff the relative cost increased by 38% in the 2023S, 44% in the 25S, and 49% in the 30S, considering the average of this cost indicator at national level. Policymakers interested in reducing inequality among states and regions are recommended to consider the variations of grid tariff and energy prices.

To evaluate actions aimed at improving the competitiveness of photovoltaic systems in terms of cost before 2023, this study conducted a sensitivity analysis to assess the impact of reductions in the prices of photovoltaic equipment on PV energy levelized costs. Figure 5 illustrates the energy generation costs

Figure 5: Levelized cost of photovoltaic systems energy before 2023, after 2023, and after reductions on the photovoltaic equipment costs



in three scenarios: Before 2023, in 2023 (when the grid tariff was implemented), and after 2023, assuming average equipment prices in the country decreased by (A) 10%, (B) 20%, (C) 30%, and (D) 40%.

It should be noted that after the start of charging the grid tariff for using the electricity grid, the equipment should suffer a reduction of at least 40% so that photovoltaic generation costs are reduced to the costs verified before 2023.

5. CONCLUSION AND POLICY IMPLICATIONS

The commencement of charging the grid tariff for the utilization of the electricity grid, as stipulated by ANEEL Normative Resolution No. 1,059/2023, had a substantial impact on the economic feasibility of on-grid photovoltaic systems (PVs) in Brazil. As these energy generators now incur additional expenses, we projected that the average discounted payback period (DPP) will raise 43% from 2023 to 2030. Simultaneously, a reduction of 30.8% in the average internal rate of return (IRR) is predicted after the start of charging for using electricity grid.

The results clearly demonstrate that the financial indicators for investing in on-grid PVs within medium-sized family homes in Brazil were very attractive prior to 2023, with an average IRR of 22.7% and a DPP of 5.0 years. However, these indicators will reach an IRR of 16.5% and a payback of 7.2 years, progressively until 2030. Based on previous literature, it is possible to investigate the impact on different residences, with the larger residences expected to be less impacted. Also, a huge variance of results was observed among states.

This outcome presents a scenario where the appeal of new investments in PVs is expected to decline in the coming years, primarily due to the impact of these new regulations. However, we emphasize that even after charging the full tariff for using the energy grid, the results still indicate the country's economic viability of on-grid PV energy generation. This viability may be increased whether, instead of individual investments, final users start to invest collectively through joint procurements. Some developed countries, such as Finland, have registered the adoption of this solution without any specific policy. However, his context may require new promotion policies to notify users about this possibility in Brazil and even legislation adaptions.

The results indicate an increasing trend in the cost of on-grid PV energy in medium-sized homes caused by ANEEL Normative Resolution No. 1,059/2023, projecting an 49.7% increase in the average levelized cost of this energy source by 2030. Consequently, a deceleration in the rate of investment in this form of energy generation in the country is expected in the coming years unless new policies aimed at incentivizing PV energy generation are introduced.

It's worth noting that this study did not conduct a sensitivity analysis to identify the key modeling variables that could contribute to reducing the cost of PV energy generation. This analysis would be important to identify which main actions or policies could be implemented to reduce the cost of PV energy, with the aim of increasing the share of this form of energy, which has a very low environmental impact, in the national matrix. Conducting such a sensitivity analysis could provide valuable insights for policymakers and stakeholders involved in the renewable energy sector.

Another recommended analysis for future work would be to apply Data Envelopment Analysis (DEA) models to evaluate the relative performance of PV energy generation in different states and benchmark best practices regarding state policies. This analysis can facilitate the prioritization of actions to expand the use of this energy source in regions that exhibit higher performance.

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APPENDIX

Table A-1: Energy rate, tax of utilization of energy company electoral grid and solar irradiance of each state considered in the analysis

State	Capital	Energy company	Energy rate US$/MWh	Grid Tariff (TUSD-Wire B) US$/MWh	Solar irradiance KWh/m²/day
SP	São Paulo	Enel SP	0.14	0.04	4.88
RJ	Rio de Janeiro	LIGHT	0.17	0.04	4.94
PR	Curitiba	COPEL-DIS	0.13	0.03	4.78
SC	Florianópolis	CELESC-DIS	0.12	0.02	4.35
RS	Porto Alegre	CEEE Equatorial	0.14	0.04	4.56
MG	Belo Horizonte	CEMIG-D	0.16	0.04	4.98
ES	Vitória	EDP ES	0.14	0.04	4.94
MS	Campo Grande	Energisa MS	0.18	0.07	4.92
GO	Goiânia	Enel GO	0.14	0.03	5.26
MT	Cuiabá	Energisa MT	0.18	0.05	5.03
TO	Tocantins	Energisa TO	0.16	0.07	5.24
BA	Salvador	Neoenergia Coelba	0.17	0.07	5.21
PE	Recife	Neoenergia Pernambuco	0.16	0.05	5.37
AL	Maceió	Equatorial AL	0.18	0.05	5.28
RN	Natal	Neoenergia Cosern	0.14	0.05	5.64
CE	Fortaleza	ENEL CE	0.15	0.06	5.65
MA	São Luís	Equatorial MA	0.13	0.06	5.21
PA	Santarém	Equatorial PA	0.18	0.08	4.87
AM	Manaus	Amazonas Energia	0.17	0.05	4.52

Table A-2: Discounted Payback and Intern Return Rate calculated for each state in each scenario

UF	Discounted payback (years)				Intern return rate (%)			
	Bef-23[1]	S23[2]	S25[3]	S30[4]	Bef-2023 (%)	S23 (%)	S25 (%)	S30 (%)
AL	3.7	4.1	4.5	4.9	29.3	25.5	24.0	22.5
MT	3.9	4.3	4.7	5.2	28.3	24.3	22.7	21.2
RJ	4.2	4.6	4.9	5.3	26.2	23.0	21.8	20.7
MS	4	4.6	5.3	6	27.5	22.2	20.2	18.4
PI	4.1	4.8	5.5	6.1	26.7	21.4	19.6	17.8
PE	4.3	4.8	5.3	5.8	25.8	21.7	20.3	18.9
PA	4	4.8	5.7	6.6	27.1	20.9	18.6	16.6
CE	4.1	4.8	5.6	6.3	26.5	21.1	19.2	17.4
BA	4.1	4.9	5.7	6.5	26.5	20.7	18.7	16.8
AM	4.7	5.4	5.9	6.3	23.2	19.6	18.4	17.2
MG	4.8	5.4	5.9	6.3	23.0	19.5	18.4	17.3
RN	4.6	5.4	6.1	6.9	24.1	19.1	17.4	15.8
TO	4.5	5.4	6.3	7.2	24.7	18.7	16.8	14.9
GO	5.1	5.8	6.2	6.7	21.4	18.2	17.3	16.3
RR	5.4	6.1	6.6	7.1	20.5	17.2	16.2	15.3
ES	5.5	6.3	6.9	7.4	20.0	16.6	15.6	14.7
SP	5.7	6.6	7.1	7.6	19.3	15.9	15.0	14.1
SE	5.4	6.6	7.4	8.2	20.5	15.6	14.2	12.9
PB	5.6	6.8	7.6	8.3	19.7	15.2	13.9	12.8
MA	5.4	6.9	7.9	8.9	20.3	14.7	13.2	11.8
RS	5.9	6.9	7.5	8	18.4	15.1	14.1	13.3
AC	5.4	7.1	8.2	9.4	20.2	14.2	12.6	11.1
PR	6.3	7.1	7.5	7.9	17.2	14.8	14.2	13.6
RO	6.2	7.6	8.4	9.1	17.7	13.5	12.4	11.5
SC	8.2	9.7	10.4	11.0	12.9	10.6	10.1	9.6

[1]B 2023: Scenario before 2023/[2]2023: Scenario 2023/≥2025: Scenario 2025/42030: Scenario 2030

Table A-3: Costs and relative costs of photovoltaic electricity calculated for each state

UF	Costs (US$/kWh)				Relative costs			
	Bef-2023	S23	S25	S30	Bef-2023 (%)	S23 (%)	S25 (%)	S30 (%)
PE	0.05	0.08	0.08	0.08	35	49	51	53
RN	0.05	0.08	0.08	0.08	37	54	57	59
CE	0.05	0.08	0.08	0.09	34	52	54	57
PI	0.05	0.08	0.08	0.09	34	51	54	56
PB	0.05	0.07	0.08	0.08	43	59	61	64
SP	0.06	0.08	0.08	0.08	44	56	58	59
RJ	0.06	0.08	0.08	0.08	34	45	47	48
PR	0.06	0.07	0.08	0.08	47	57	58	59
RS	0.06	0.08	0.09	0.09	45	58	59	61
MG	0.06	0.08	0.08	0.08	38	50	52	54
ES	0.06	0.08	0.08	0.08	43	55	57	58
MS	0.06	0.09	0.10	0.10	33	51	53	55
GO	0.06	0.07	0.07	0.08	40	52	54	55
MT	0.06	0.08	0.09	0.09	32	46	48	49
TO	0.06	0.09	0.09	0.10	36	56	59	61
BA	0.06	0.09	0.09	0.10	34	53	56	58
AL	0.06	0.08	0.08	0.08	31	44	46	47
MA	0.06	0.08	0.09	0.09	42	61	64	67
PA	0.06	0.10	0.10	0.11	33	54	57	59
AC	0.06	0.10	0.10	0.10	42	63	66	68
RO	0.06	0.08	0.09	0.09	46	62	64	66
RR	0.06	0.08	0.08	0.09	42	54	55	57
SE	0.06	0.08	0.08	0.09	42	59	61	64
SC	0.07	0.08	0.08	0.08	57	66	68	69
AM	0.07	0.09	0.09	0.09	38	51	53	54

[1]B 2023: Scenario before 2023/[2] 2023: Scenario 2023/[3]2025: Scenario 2025/[4]2030: Scenario 2030. [5]Relative costs: Photovoltaic costs/energy price rated by the energy supplier company