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THE ENERGY INJUSTICE OF HOUSEHOLD SOLAR ENERGY: EVIDENCE OF ADOPTION INEQUALITY AND TARIFF IMPACTS FROM BRAZIL

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Gabriel Konzen

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Doctoral Dissertation presented to the Graduate Program in Public Policies, Strategies, and Development at the Federal University of Rio de Janeiro, as a partial requirement for the degree of Doctor in Public Policies, Strategies, and Development.

Supervisor: Prof. Dr. Nivalde José de Castro

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ABSTRACT

KONZEN, Gabriel. **The energy injustice of household solar energy: evidence of adoption inequality and tariff impacts from Brazil**. Rio de Janeiro, 2025. Dissertation (Ph.D. in Public Policies, Strategies, and Development) – Institute of Economics, Federal University of Rio de Janeiro, Rio de Janeiro, 2025.

The decentralization of energy systems is a global trend that has been increasingly consolidated, particularly through the expansion of distributed photovoltaic generation (DG). Despite the benefits associated with this form of generation, concerns have emerged regarding energy justice. In developing countries, there is a lack of studies exploring the extent of inequality in the adoption of DG, as well as the effects of incentive policies on non-adopting consumers. In this context, this dissertation aims to fill this gap by investigating whether the expansion of DG has occurred in accordance with the principles of energy justice, with a focus on the Brazilian case. The dissertation comprises three essays that address complementary aspects. The first presents an international systematic review that reveals persistent patterns of distributive injustice associated with DG, particularly regarding the concentration of benefits among higher-income groups. The second essay compares the experiences of Brazil and Australia, employing descriptive statistics, a Solar Gini Index, and regression models. The findings reveal a high level of inequality in DG adoption in Brazil, especially when compared to the Australian case. Moreover, both countries showed little improvement in this regard over the years. The third essay analyzes the tariff impacts of the Brazilian regulatory transition from the net metering model to net billing. The results suggest that the new model tends to reduce tariff impacts, though not eliminate them. The analysis indicates that promoting a more just energy transition requires reforming the tariff structure, directing subsidies to vulnerable groups, and investing in shared generation programs. Thus, this dissertation demonstrates that, in the absence of well-designed public policies, the transition may deepen socioeconomic inequalities, underscoring the importance of incorporating energy justice as a key element in energy policy design.

Keywords: Energy justice; Inequality; Solar Energy; Distributed generation; Electricity Tariffs

RESUMO

KONZEN, Gabriel. **The energy injustice of household solar energy: evidence of adoption inequality and tariff impacts from Brazil**. Rio de Janeiro, 2025. Tese (Doutorado em Política Públicas, Estratégia e Desenvolvimento) – Instituto de Economia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2025.

A descentralização dos sistemas energéticos é uma tendência global, que vem se consolidando especialmente com a expansão da geração distribuída fotovoltaica (GD). Apesar dos benefícios associados a essa forma de geração, surgem preocupações relacionadas à justiça energética. Nos países em desenvolvimento, há escassez de estudos que explorem o grau de desigualdade na adoção da GD, bem como os efeitos das políticas de incentivo sobre os demais consumidores. Nesse contexto, esta tese busca preencher essa lacuna, investigando se a expansão da GD tem ocorrido em conformidade com os princípios da justiça energética, com ênfase no caso brasileiro. A tese é composta por três ensaios que abordam aspectos complementares. O primeiro apresenta uma revisão sistemática internacional que revela padrões persistentes de injustiça distributiva, especialmente no que diz respeito à concentração dos benefícios entre os grupos de maior renda. O segundo ensaio compara as experiências do Brasil e da Austrália, utilizando estatísticas descritivas, um índice de Gini Solar e modelos de regressão. Os resultados mostram alta desigualdade na adoção de GD no Brasil, sobretudo frente ao caso australiano. Adicionalmente, ambos os países apresentaram pouca melhora nesse quadro ao longo dos anos. O terceiro ensaio analisa os impactos tarifários da transição regulatória brasileira, do modelo de net metering para o net billing. Os resultados indicam que o novo modelo tende a reduzir os impactos sobre as tarifas, mas não a eliminá-los. A análise sugere que, para promover uma transição energética mais justa, é fundamental reformar a estrutura tarifária, direcionar subsídios a grupos vulneráveis e investir em programas de geração compartilhada. Assim, esta tese mostra que, sem políticas públicas bem desenhadas, a transição pode aprofundar desigualdades socioeconômicas, reforçando a importância de considerar a justiça energética como um elemento no desenho das políticas do setor energético.

Palavras-chave: Geração distribuída; Justiça energética; Tarifas; Desigualdade; Energia solar

SUMMARY

1 INTRODUCTION

The energy transition is presented as a fundamental solution to mitigating the impacts of climate change on Earth (Lee; Birol, 2020). In this context, decentralization is regarded as one of the pillars of the energy transition, alongside decarbonization and digitalization (MME/EPE, 2020a). According to EPE (2018), Distributed Energy Resources (DER) hold significant disruptive potential, with the capacity to profoundly transform traditional power systems. These resources enable more active societal participation in the electricity sector and may offer benefits such reduction in energy losses and enhanced reliability in energy supply. However, their integration also presents various challenges. One of the main challenges concerns the current institutional design of the electricity sector and the need for its modernization in order to align with this new paradigm, thereby enabling the harmonious coexistence of centralized and distributed resources (MME/EPE, 2020b, p. 242).

Among the various types of Distributed Energy Resources (DER), distributed generation (DG) stands out, having gained global popularity—particularly through photovoltaic (PV) solar energy. Indeed, this source has led the addition of power capacity in recent years, surpassing all other renewable and fossil sources (IRENA, 2025). Moreover, 45% of all deployed photovoltaic capacity is in the form of DG (IEA PVPS, 2024). The successful expansion of photovoltaic distributed generation has been strongly supported by the implementation of public policies that combined robust regulatory frameworks, research and development (R&D) in new technologies, and strategic economic incentives. International experience shows that mechanisms such as feed-in tariffs and net-metering policies have been critical in scaling up residential adoption (Lemay; Wagner; Rand, 2023; Nguyen et al., 2023). Public and private R&D, in turn, has been identified as the primary driver of the historical reduction in photovoltaic module prices (Kavlak; McNerney; Trancik, 2018).

However, despite the growth and associated benefits of the expansion of this generation modality, concerns have been raised regarding "energy justice" and access to such technologies. The concept of energy justice is defined by Sovacool and Dworkin (2015) as a system that fairly distributes the benefits and burdens of energy services, ensuring representative and impartial decision-making processes. In the case of photovoltaic distributed generation, demographic inequality is particularly relevant, as highlighted by Sovacool et al. (2022), given that income and wealth strongly influence the diffusion pattern of photovoltaic installations. Thus, the development of DG goes beyond mere technological availability, requiring institutional frameworks that incorporate regulatory innovation, smart incentives, and a commitment to energy justice.

In Brazil, the modality of micro and mini distributed generation (DG[1]) was initially regulated by ANEEL—the Brazilian regulatory agency—through Normative Resolution No. 482/2012 (REN 482), which allowed any consumer to generate their own electricity. Additionally, the resolution established the Electric Energy Compensation System (SCEE), enabling surplus energy to be exported to the distribution grid, generating electricity credits (kWh) that could be used within a period of up to 60 months. Internationally, this compensation model is known as net metering.

The compensation model implemented, combined with the quality of national solar resources, the level of final electricity tariffs, and the reduction in the cost of PV equipment, has made DG a highly attractive investment in Brazil. In fact, there has been a significant increase in the number of installations, which by the end of 2024 had surpassed 3 million DG systems, totaling approximately 36 GW of installed capacity. Of these systems, more than 99.9% are photovoltaic (ANEEL, 2025d). However, this dissertation considers the possibility that such investments have been concentrated primarily among higher-income households. According to the Diffusion of Innovations Theory (Rogers, 2003), it is to some extent expected that a new technology, in the early stages of its diffusion, would be adopted by individuals with higher income (among other characteristics). This condition allows innovators and early adopters to assume greater risks and invest at a time when there is still limited information and social validation of the technology. On the other hand, after fifteen years of DG implementation in Brazil, it is reasonable to assess whether this technology has, in fact, become more democratized across the country.

The interest in analyzing the distribution of DG system adoption in Brazil gains further relevance due to the design of the net-metering model implemented in the country, in which the prosumer (a consumer who also generates electricity) is exempt from paying for the use of transmission and distribution systems, as well as for sectorial charges. Since the tariff is calculated as the ratio between the required distribution revenue and the billed market, the resulting costs are borne by other consumers through increases in electricity tariffs (Eid et al.,

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[1] Although there are different definitions for distributed generation, in this document the term "distributed generation" and the acronym "DG" will be used, when referring to Brazil, to denote the model initially regulated by ANEEL's Normative Resolution No. 482/2012 and subsequently by Law No. 14,300/2022.

2014a). Indeed, ANEEL estimates that in 2024, for example, distributed generators received a total subsidy of BRL 11.6 billion (approximately USD 2 billion) (ANEEL, 2025a).

In 2022, following extensive debates, Law No. 14,300 was enacted on January 6, 2022, effectively transforming the model previously regulated by ANEEL's Normative Resolution No. 482 into federal law. Under this legislation, the original incentive framework was preserved until 2045 for those who submitted a DG system connection request to the distribution utility before the beginning of 2023. Starting in 2023, new generators injecting electricity into the grid began receiving progressively lower compensation, reflecting the need to pay for the use of the distribution network. From 2029 onward, the energy injected by new generators will be compensated based on a cost-benefit calculation for the electricity sector. According to IRENA's (2019), definition, the model to be implemented from 2029 onward can be classified as a net-billing scheme, as the surplus energy will be valued at its actual worth to the system. It is worth noting that similar transitions have been observed in other countries, aimed at reducing subsidies and promoting a more sustainable expansion of DG (IRENA, 2019).

Despite the changes to the compensation model, it is hypothesized that DG will continue to exert upward pressure on electricity tariffs, as part of the generation will remain subsidized. As previously mentioned, a portion of existing prosumers will retain the original incentive framework until 2045. Additionally, the share of generation that is self-consumed and not injected into the grid also contributes to a reduction in the billed market, requiring tariff increases to ensure coverage of the fixed costs of the electricity sector. On the other hand, the way in which subsidies are allocated within electricity tariffs varies by consumer class. For example, low-income households are exempt from paying certain sectorial charges, including those related to distributed generation subsidies. Therefore, a combination of factors must be quantified to fully understand the net impact on consumers.

In this context, the main objective of this study is to assess whether the expansion of distributed electricity generation is being carried out in accordance with the principles of energy justice, with particular emphasis on the Brazilian case. Drawing on the definition of energy justice by Sovacool and Dworkin (2015), inequality in the adoption of distributed generation and the distribution of incentive costs emerge as key elements of this research. Accordingly, the study seeks to answer the following research questions:

a) Is there inequality in the uptake of residential DG systems?
b) If there is inequality, does it decrease over time?
c) Are there regressive impacts from DG incentive policies?

d) What is the expected tariff impact associated with the transition from the net-metering to the net-billing compensation model?

e) What recommendations are given to reduce the rooftop PV adoption inequality and the regressive impacts (if applicable)?

Based on the answers to these questions, this dissertation aims to support decision-makers in the design and implementation of fairer energy policies. The study contributes to the energy justice framework by shedding light on the dynamics of DG expansion from both distributional and cosmopolitan perspectives—particularly relevant as the Brazilian case, representative of a developing country, is compared to those of developed nations. Additionally, the research offers insights for the electricity sector regulation and tariff design processes in the context of increasing penetration of distributed energy resources.

1.1 Structure of the dissertation and presentation of the essays

To address the main objective of the dissertation and to answer the specific research questions, the work has been structured in the form of three essays. In this way, the expansion of distributed generation is analyzed from different perspectives, although all essays share the common thread of energy justice. Following the introduction, the three essays are presented in full. General conclusions are provided in Chapter Five, the references used throughout this document are listed in Chapter Six, and the published articles and other supplementary material are included in the appendices at the end of the document.

The connection of each essay to the overall theme, as well as the rationale for their order of presentation, is explained below.

1.1.1 First essay

Title: The energy injustice of household solar energy: A systematic review of distributional disparities in residential rooftop solar adoption.

Inequality in the adoption of grid-connected residential photovoltaic systems is one of the fundamental elements of energy injustice in the global expansion of distributed generation. Internationally, countries with a longer history in the development of this technology have already faced the need to assess solar energy incentive policies from a distributive perspective. This international experience, therefore, can help inform the Brazilian context and provide insights into the current state of research in the field.

In this regard, the aim of the first essay is to conduct a qualitative systematic literature review to establish the state of the art and provide a theoretical foundation for the subsequent analyses. More specifically, this essay seeks to answer, at the international level: (a) whether there is unequal distribution in the adoption of grid-connected residential DG systems; (b) whether such inequality decreases over time; (c) whether DG incentive policies have regressive impacts; (d) what recommendations have been proposed to reduce adoption inequality and mitigate regressive effects; and (e) what methods are employed by researchers to address these questions.

In addition to offering conclusions on the global situation, this essay is important for identifying the methodologies most commonly used by scholars, thereby serving as a methodological reference for the development of the following essays in the dissertation. Furthermore, the review provides a snapshot of the geographical distribution of existing studies, highlighting that developing countries—particularly Brazil—have received limited attention in the published literature to date, which underscores the relevance of this research.

1.1.2 Second essay

Title: Shining a Light on Disparities: A Comparative Analysis of Residential Photovoltaic Adoption Inequality in Australia and Brazil.

The first essay identified only three studies that examined aspects of inequality in the adoption of DG in Brazil. This suggests that the topic has been relatively underexplored in the country. Additionally, a methodological limitation was observed in these studies: they rely on aggregated data at the state, municipal, or census tract level (Chueca et al., 2023; Costa; Santos, 2020; De Freitas, 2022). The literature has shown that analyses based on aggregated data may yield different results compared to studies conducted at the individual or household level (Best; Chareunsy, 2022).

In contrast to Brazil, as demonstrated in the first essay, Australia has an extensive body of literature on the characteristics of rooftop solar adopters and the inequality associated with PV adoption. Moreover, Australia ranks among the global leaders in PV capacity per capita. Although a significant number of studies on rooftop solar adoption in Australia already exist, there remains considerable scope for further contributions to this field. First, a comparative analysis between the two countries adds value by contextualizing results(Konzen; Best; De Castro, 2024). By employing similar variables, datasets, and methods, this study facilitates meaningful comparisons across different contexts. Second, the analysis expands on previous research by exploring the evolution of PV adoption inequality. In addition to examining the adoption probability gap in percentage points (Best; Chareunsy; Taylor, 2023a, 2023b), two additional approaches are used. Changes in the distribution of adopters among income quintiles are scrutinized, and a Solar Gini index is proposed to facilitate cross-country comparisons of PV inequality and its evolution over the years. Thirdly, the assessment of inequality in developing countries, particularly using household-level data, remains limited in the existing literature (Konzen; Best; De Castro, 2024). The case study of Brazil aims to address this gap.

This essay, therefore, provides an overview of the inequality in the adoption of distributed generation systems in Brazil. The comparison with Australia, along with the discussion based on the socioeconomic conditions of both countries and the differences in their energy policies, contributes to a deeper understanding of the results and their implications for energy justice.

1.1.3 Third essay

Title: From net-metering to net-billing: evaluating the tariff effects of distributed generation in Brazil.

The second essay aims to characterize the profile of distributed generation adopters in Brazil in recent years and to highlight the role of income in adoption. However, this snapshot captures only part of the inequality dimension related to the diffusion of this technology in Brazil. Another relevant aspect concerns the tariff impacts of its expansion, which are closely linked to the incentive policy adopted in the country. As previously mentioned in this introduction, the transition from the net-metering to the net-billing model will change the subsidy dynamics associated with DG in Brazil. Furthermore, there are factors that exert opposing effects on tariffs—some increasing and others decreasing them—that must be carefully assessed to determine the net impact on consumers. In the context of energy justice, it is essential to separately analyze the effects on conventional electricity tariffs and on those applied to low-income consumers.

Although some authors have conducted research related to this topic (Da Silva; Rato, 2024; Iglesias; Vilaça, 2022; Martins; Branco; Hallack, 2022), none have assessed the effects beyond 2028, when the net-billing model will come into effect. Moreover, these studies were limited to a few distribution companies and did not explore the impacts on low-income consumers. In this context, the present essay seeks to address these gaps by offering the following contributions to the existing literature: (i) the analysis adopts the tariff calculation methodology approved by ANEEL, ensuring greater methodological rigor; (ii) both historical impacts (under the net-metering model) and future impacts, considering the upcoming net-billing regime, are evaluated; (iii) a disaggregated analysis of the impacts on conventional consumers and low-income consumers is provided, highlighting issues related to energy justice; and (iv) the methodology is applied to 32 distribution companies, covering 90% of electricity consumers in Brazil.

This essay complements the previous analyses by evaluating the tariff impacts of distributed generation (DG) deployment in Brazil, particularly in the context of the transition to the net-billing model. In other words, it aims to assess whether the change in the compensation mechanism can prevent the cross-subsidies currently associated with DG adoption. The impacts on electricity tariffs for low-income consumers are explicitly examined, with the intention of shedding light on the effects for this specific group. Additionally, drawing on existing literature, the essay proposes an alternative tariff design that better aligns with the ongoing decentralization of power systems. Although the analysis focuses on the Brazilian case, the findings may also provide useful insights for other countries facing similar challenges with the integration of distributed generation.

2 FIRST ESSAY: THE ENERGY INJUSTICE OF HOUSEHOLD SOLAR ENERGY: A SYSTEMATIC REVIEW OF DISTRIBUTIONAL DISPARITIES IN RESIDENTIAL ROOFTOP SOLAR ADOPTION

ABSTRACT

Power generation from grid-connected residential photovoltaic (PV) systems has been widely recognized worldwide as an integral component in the energy transition. However, concerns remain about whether its costs and benefits have been fairly distributed in our society. This systematic review was conducted using 87 articles to explore inequalities in the adoption of rooftop PV systems in the world and its distributive impacts. There is strong evidence that adoption occurs predominantly among affluent households, and although some studies show a reduction in concentration over time, adoption remains uneven in most places. Furthermore, the incentive policies for rooftop PV have regressive characteristics, as they especially benefit the wealthiest, while their costs disproportionately affect the most vulnerable households. To address this situation, the literature recommends targeting subsidies to lower-income households, encouraging community solar facilities, and better publicizing the characteristics of the incentive programs, especially in vulnerable communities. In addition, using more cost-reflective electricity tariffs and replacing the feed-in tariff mechanism with market-oriented policies can help reduce inequalities. Finally, the essay outlines future research agendas to expand upon the insights gained from this study.

Keywords: Energy justice; Solar energy; Distributed generation; Rooftop solar; Systematic review

2.1 Introduction

Solar photovoltaic technology (PV) has become paramount in the global energy transition, reaching the 1 TW mark of installed capacity in 2022. Of this capacity, 40% is in distributed generation systems (DGPV). That is, systems connected to the distribution network or directly in consumer units. Of this group, approximately 130 GW are in residential rooftop systems, spread over approximately 25 million households around the world (IEA, 2022). With the rapid decline in the price of PV systems observed in recent years, countries have begun to reduce subsidies for photovoltaic generation, especially for utility-scale plants. However, distributed generation systems also remain heavily dependent on incentive policies. In 2021, for example, 86% of the DGPV installed capacity in the world was developed under some financial incentive program (IEA PVPS, 2022).

Worldwide, the main policies to stimulate the adoption of grid-connected distributed generation are as follows: (i) Feed-in Tariffs (FiT), which is a payment for the electricity fed into the grid at a predefined price and guaranteed during a fixed period; (ii) Net-metering, which allows generators to receive a financial credit on their electric bills for any surplus energy injected into the grid; (iii) Net-billing, which is similar to net-metering, but in which the injected electricity is not valued by the usual consumption rate, but by a tariff that reflects the real value of the generation to the grid; and (iv) rebates and tax credits, which are subsidies that cover part of the initial investment for the installation of a PV system (IEA PVPS, 2022; IRENA, 2019).

From the point of view of the residential consumer, investing in distributed generation brings several benefits, such as reducing the cost of electricity, protecting against future increases in electricity tariffs and increasing the value of the home (Brinkley; Leach, 2019). However, despite the benefits associated with deploying this kind of technology, there are concerns related to energy justice. The concept of energy justice is defined by Sovacool and Dworkin (2015) as "a global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision-making". To delve deeper, drawing upon the energy justice framework established by McCauley et al. (2019), the adoption of distributed generation worldwide and the incentive policies supporting it can be evaluated through the lenses of various dimensions (i) distributional justice (how resources, costs, and benefits are allocated across different stakeholders); (ii) recognition justice (post-distribution reflection on where and how inequalities may emerge within the energy system); (iii) procedural justice (the right to meaningful participation in energy-related decisions and institutions) and (iv) cosmopolitan justice, which applies the previous concepts to all human being in all nations. The dimension of distributional justice is particularly pertinent to the topic of rooftop solar. This concern can also be described as demographic inequity, as highlighted by Sovacool et al. (2022), who emphasize that "income and wealth (and in some places, race) strongly shape the diffusion patterns for things such as EV ownership or solar panel installations.".

It is essential to underscore that energy justice goes beyond mere conceptualization and categorization; it serves as a decision-making framework that can inform and influence energy practices, policymaking, and public choices (Sovacool et al., 2016). However, it's worth noting that there are varying perspectives among scholars regarding the motivations behind energy justice. While some argue that justice is an inherent value rooted in egalitarian ethics, others view energy justice as a means to achieve specific objectives, such as promoting economic development in communities or generating profits for businesses (Bidwell; Sovacool, 2023).

This discussion of energy justice in the context of solar energy is relevant mainly due to the expectation of growth in the DGPV systems in the coming years. The International Energy Agency (IEA) (2022) considers fundamental the growth in the number of households with solar energy to completely decarbonize the energy sector. In its Net Zero Emissions by 2050 scenario, IEA projects the world to have 100 million households with PV by 2030. That is, a four-fold increase in the number of residential rooftop solar systems compared to the 2022 figure.

Several articles explored aspects related to energy justice issues in the DGPV adoption in different contexts. For instance, Alipour et al. (2021), conducted a review of 173 studies examining the adoption behavior of residential solar PV systems, revealing mixed effects of income as a predictor of adoption. However, this study encompassed not only grid-connected systems but also off-grid systems, which are generally installed under different policies. Hence, our study is centered on grid-connected residential PV systems, with the objective of examining not just the impact of income at a specific moment but also the progression of inequality and the economic consequences of incentive policies on diverse socioeconomic groups. Furthermore, this review can uncover shared trends and disparities in outcomes, recognize research trends, and pinpoint prospects for future investigations in this domain. Moreover, employing a systematic review approach can mitigate selection bias and enhance the reliability of our findings (Snyder, 2019).

In this context, this essay seeks to evaluate, through a systematic review, the adoption of DGPV systems within the energy justice framework (McCauley et al., 2019; Sovacool et al., 2016; Sovacool; Dworkin, 2015). In order to retain focus and depth, we have limited the analysis to the distributional aspect of the framework, i.e., assessing the deployment of DGPV particularly with regard to the equitable distribution of costs and benefits across society. More specifically, the paper aims to explore this topic by answering the following questions:

1. Is there inequality in the uptake of residential grid-connected PV systems?
2. If there is inequality, does it decrease over time?
3. Are there regressive impacts from DGPV incentive policies?
4. What recommendations are given to reduce the rooftop PV adoption inequality and the regressive impacts (if applicable)?
5. What methods are used by authors to answer these questions?

Inequality can be defined as “the phenomenon of unequal and/or unjust distribution of resources and opportunities among members of a given society” (Koh, 2020). Thus, in line with the definition, and given the scope of our research, we refer to inequality as the difference between solar panel uptake across economic distributions (income, wealth, or similar index). The term ‘regressive’, on the other hand, refers to policy costs that are paid disproportionately by low-income households (Zachmann; Fredriksson; Claeys, 2018).

Consequently, the previous research questions serve as a foundation for the subsequent analysis, aimed at offering evidence and suggestions to academics and decision-makers to help build a fairer energy transition.

2.2 Methods

A systematic review of the literature was conducted to answer the research questions. It uses predefined selection criteria to find empirical evidence to answer certain questions or hypotheses (Snyder, 2019). In this paper, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework (Moher et al., 2010) is utilized as the foundation for the review.

2.2.1 Eligibility criteria

Based on the research questions presented in the previous section, we defined the following eligibility criteria:

1. Studies that evaluate aspects of inequality, distributive impacts, effect of income or wealth, and similar topics in the adoption of photovoltaic systems. The specific keywords to identify the relevant studies into our search strategy are detailed below in sub-section 2.3.
2. With focus on the grid-connected systems for residential applications. Grid-connected systems represent most of the distributed generation market, even in Africa and Asia, continents known for the greater need for electrification (IEA PVPS, 2022).
3. Published in English language.
4. In peer-reviewed journals.

2.2.2 Exclusion criteria

During the first step, we established specific exclusion criteria to be applied to our initial search strategy, which are detailed below. We kept the initial list short to avoid the potential exclusion of relevant articles, with subsequent manual selection.

a) Installations other than solar PV, such as solar thermal systems or other distributed generation sources such as biogas, wind, or hydro.
b) Off-grid systems. These systems are distinct products, which generally use batteries and are built to meet specific needs. For example, portable flashlights and small devices, such as mobile phone chargers, represented 83% of off-grid solar solutions sold in 2021 (Li et al., 2018).

We subsequently conducted a further manual analysis of articles and used additional exclusion criteria:

a) Qualitative analyses, such as interviews with experts or opinion articles.
b) Focus exclusively on rural systems. In the literature, studies with an exclusive focus on rural areas are often associated with off-grid projects[2] and, therefore, were also excluded from the analysis.
c) Analysis for renewable sources in general, with no focus on distributed generation.
d) Based on the intention to adopt DGPV or forecasts, not on actual adoption data. Insights on intended uptake were provided by Schulte et al. (2022).
e) Focus on solar cooking.
f) Impact assessments without distributional analysis.
g) Studies with no focus on economic inequality (e.g. racial disparities in rooftop PV adoption).
h) Studies on the economic feasibility of investment in DGPV.
i) Studies evaluating the technical potential of DGPV penetration, as the area available on roofs.
j) Other topics not related to research.

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[2] One exception is the Photovoltaic Poverty Alleviation Projects in China, which are developed in rural areas but connected to the grid. Residents receive subsidies for the installation of photovoltaic systems and later receive payment for the energy generated through FiT (Li et al., 2018). This model has helped reduce poverty in rural areas of China (Zhang et al., 2020).

2.2.3 Search strategy

Based on the previous eligibility and exclusion criteria, we developed an initial string to identify relevant studies. Searches were conducted in the Scopus and in Web of Science (WoS) databases, covering articles indexed up to October 05, 2023. The string used in Scopus is displayed in sequence. An analog string was used on the WoS database.

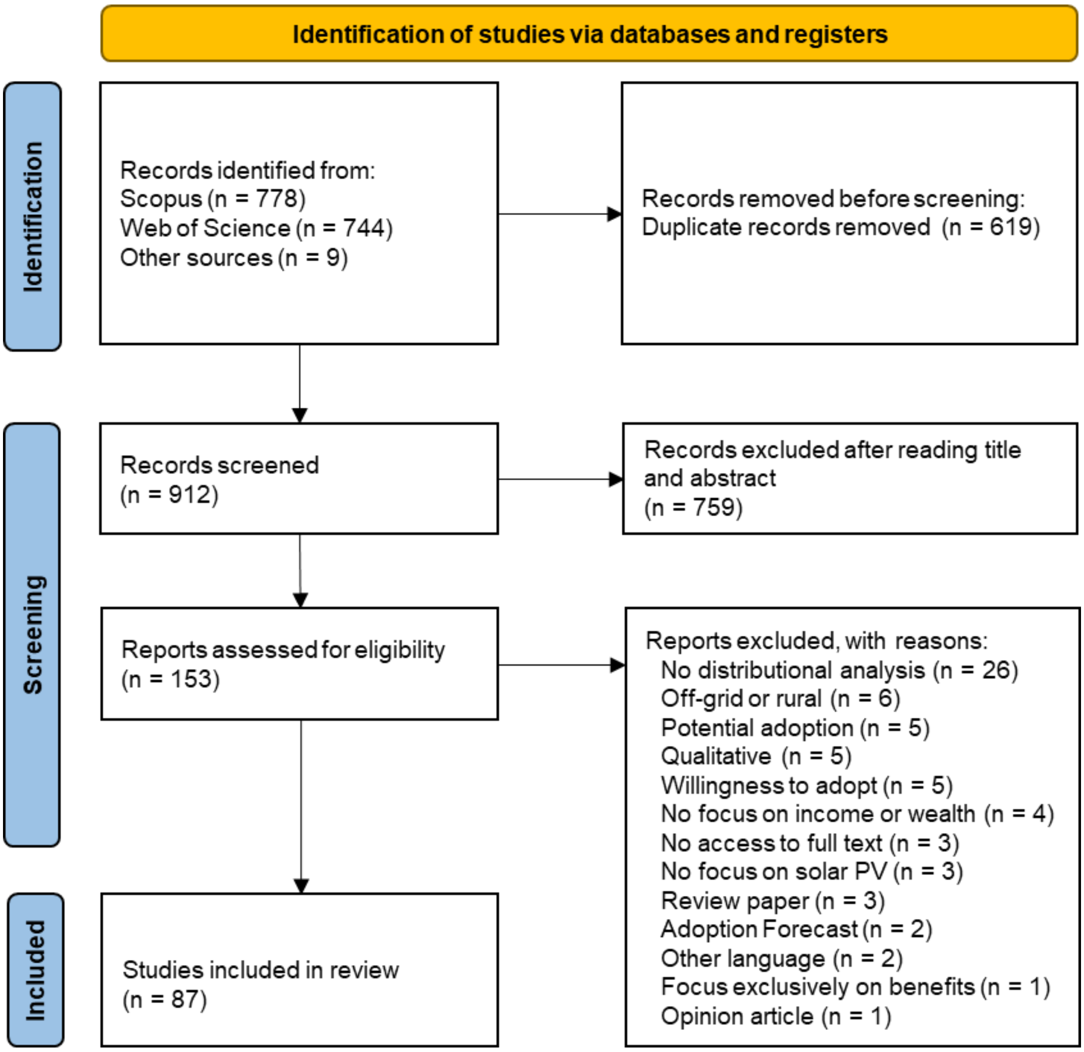
*TITLE-ABS-KEY ((*equit* OR *equality OR wealth* OR *distributive OR distributional OR regressive OR disparities OR justice OR income) AND ("feed-in" OR "net-metering" OR "self consumption" OR solar OR photovoltaic OR pv OR "distributed energy" OR "distributed generation") AND (household OR residential OR home OR consumers OR customers OR prosumers) AND NOT (water OR "solar home system" OR "off grid" OR thermal)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English"))*

After excluding duplicates, this initial search on both databases yielded 903 articles. In addition, nine external articles were incorporated based on the authors' expertise and recommendations from reviewers.

2.2.4 Data extraction and manual analyses.

After an initial analysis of titles and abstracts, the review was restricted to 153 articles. Then, a preliminary reading of the complete texts was made, and some more papers were eliminated, leaving 87 articles for the final analysis. Figure 1 shows the process of selecting articles during the systematic review. Each article underwent manual inspection and was categorized based on its stated objectives, primary methods, geographical location, level of analysis, results, conclusions, and limitations. Due to the heterogeneity of the methodologies and variables used by the studies, it was not possible to summarize the results quantitatively in a meta-analysis study. Therefore, based on the inspection of the reviewed texts, the research questions of this review will be answered qualitatively.

Figure 1 - Process of reviewed papers selection



Source: Own elaboration.

2.2.5 Limitations

While this review provides a comprehensive analysis of the economic inequality in the adoption of grid-connected residential solar systems, it is important to acknowledge and address certain limitations inherent in the scope and methodology of this study.

a) First, it is worth mentioning that during the analysis of the articles, emphasis was placed on the aspect of economic inequality. Several articles explored effects related to age, race, education, gender, and housing characteristics, among others, which were not the object of analysis of this review.
b) Given the exclusion criteria used, the conclusions of this review should be interpreted with the disclaimer that they do not apply to off-grid and rural incentive policies. This selection criteria also naturally introduced a geographical

bias towards developed countries given the prevalence of off-grid and rural solar applications in developing economies. For a review of the expansion of off-grid systems and its effect on economic development, see the work by Radley and Lehmann-Grube (2022).

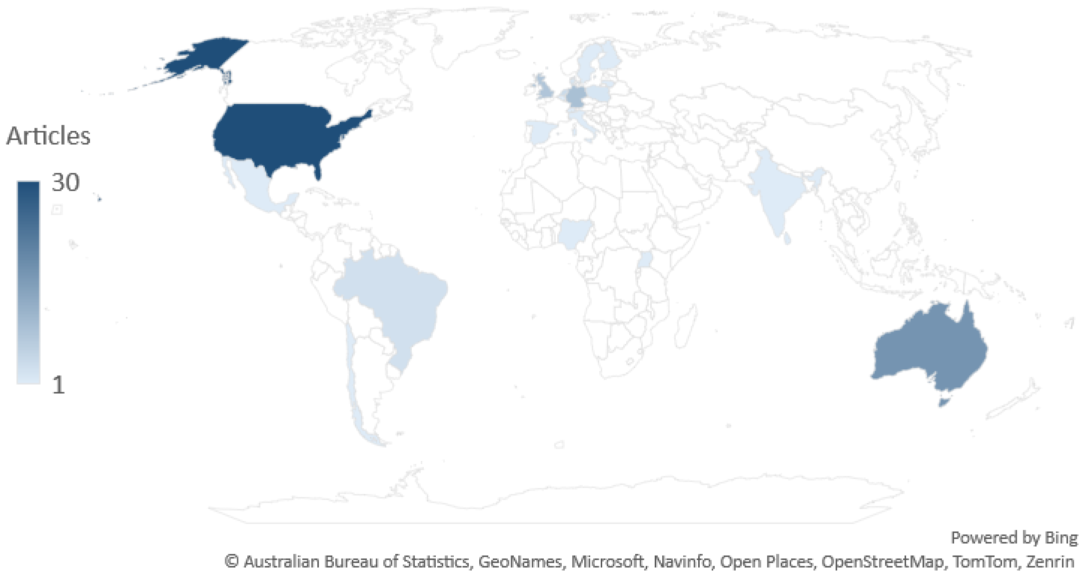
c) While we made a concerted effort to encompass various synonyms for each search keyword, using two databases, and adding nine external articles, it's important to recognize the potential limitation of not including all relevant literature within the scope of this review.
d) The data collection and paper analysis were undertaken by a single author, which could introduce bias into the review. However, to mitigate this bias, we followed the PRISMA framework during the review process.
e) Finally, our review did not use a weighting mechanism for the assessed articles based on their methodological rigor, a practice deemed desirable for enhancing the rigor of systematic reviews (Sovacool; Axsen; Sorrell, 2018). Nevertheless, throughout this document, we address specific limitations of individual studies, offering a nuanced discussion that remains pertinent to the formulation of our conclusions.

2.3 Results and discussion

2.3.1 Main characteristics of the studies and methodologies

Among the reviewed articles, there is a concentration of analyses in developed countries, such as the USA, Australia, Germany, and the United Kingdom. In fact, 91% of the studies cover developed countries, and only eight articles focus on developing countries (Figure 2).

Figure 2 - Number of articles which cover each country

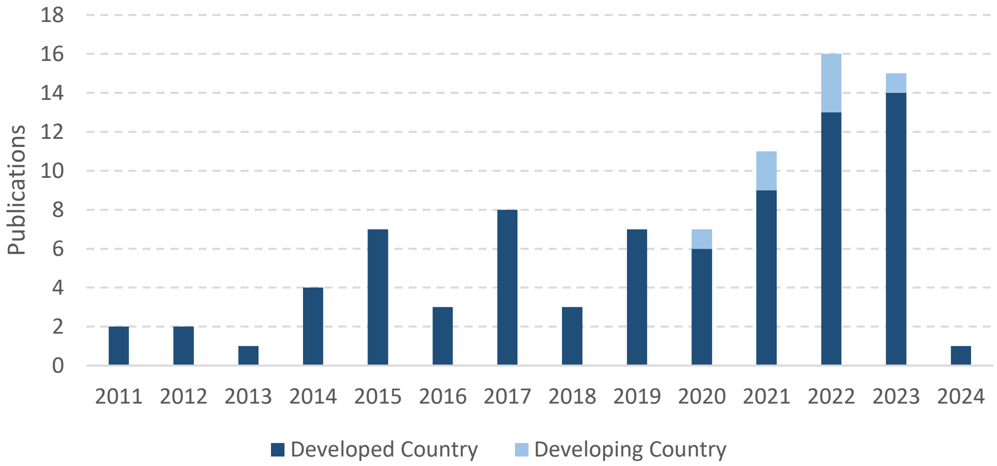


Source: Own elaboration.

In this context, it's worth noting that developing nations typically exhibit higher income inequality compared to advanced economies (Makhlouf, 2023). Consequently, studying energy justice concerns in these countries is even more relevant given the larger income gap among their societies. Another discussion can be drawn from the energy justice framework, specifically concerning the cosmopolitan justice tenet. As defined by McCauley et al. (2019), "cosmopolitan justice accepts that all human beings have equal moral worth and that our responsibilities to others do not stop at borders.". Hence, there is an opportunity to explore disparities in the uptake of DGPV in a more geographically diverse manner.

About 60% of the studies performed nationwide analyzes, while 40% did localized studies, exploring only some states or municipalities, for example. In relation to the year of publications, there has been growth in the last decade, especially from 2021, demonstrating the increased interest in the subject (Figure 3). The main characteristics of each study can be seen in the Appendix B.

Figure 3 - Distribution by year of 87 publications under review. Data up to October, 2023



Source: Own elaboration.

2.3.1.1 Main methods

This section presents the main methods used by the authors in their works. It is worth mentioning that we emphasized the methods used to answer the research questions of this review. This analysis did not include additional methodologies used exclusively to answer other research questions. Additionally, auxiliary methods, such as data imputation or estimation of PV generation, were not included in this review.

As shown in Table 1, among the studies that evaluated the relationship of income with the adoption of residential PV systems, there is a preference for using econometric regression methods. Among the regression models, most studies used traditional models, such as the Ordinary Least Squares (OLS), Probit, or Logit methods. In general, studies that evaluated the relationship at an aggregate spatial level (census tract or zip code, for example) preferred OLS. In this case, the dependent variable is usually a solar energy penetration index (for example, the percentage of households with DGPV). On the other hand, studies whose unit of analysis was the household preferred Probit or Logit models because the dependent variable is usually binary (it has or does not have solar energy).

Table 1 - Methods used to evaluate the inequality in DGPV adoption

Method	No. of Papers
Regression	53
Distribution Charts	18
Survey/Interview	8
Correlation	5
Statistical Test	4
Cluster Analysis	3
Diffusion Model	3
Machine Learning	3
Inequality Metrics	2
Piecewise Structural Equation Modelling	2
Cost-benefit Analysis	1
Electricity Market Model	1
Simulation	1
Structural Model	1
Time-series Analysis	1

Note: The sum is greater than the number of articles due to the use of multiple methods in some articles.

In addition to regression methods, several articles used descriptive statistics to show the distribution of PV installations by income quantile. This method, here as "Distribution Charts", in some cases requires joining socioeconomic databases (income per census tract, for example) with locational databases of PV systems. In other cases, the authors used databases with data per household that have income information and adoption of PV systems (or receipt of subsidies for solar energy). In these cases, the elaboration of distribution charts is more direct. It is worth mentioning that most of the authors used secondary data to carry out the studies. Only eight studies collected the data through their own surveys or interviews (Bao et al., 2020; Etongo; Naidu, 2022; Keady et al., 2021; Ruokamo et al., 2023; Simpson; Clifton, 2017; Thompson et al., 2021; Varela-Margolles; Onsted, 2014; Vasseur; Kemp, 2015).

A group of studies used correlation techniques to verify the relationship between income and PV adoption, such as Pearson's coefficient or Cramér's V (Costa; Santos, 2020; Fournier et al., 2020; Grösche; Schröder, 2014; Lukanov; Krieger, 2019; Yu et al., 2018). Another group used statistical tests (Kruskal-Wallis H, ANOVA, Randomization Test, Chi-squared) to verify differences in socioeconomic characteristics between adopters and non-adopters (Griffith; Higgins; Turner, 2014; Keady et al., 2021; Reames, 2020; Sigrin; Pless; Drury, 2015). As shown in Table 1, other techniques were also used but for fewer studies.

Regarding the methods used to assess inequality over time, it is observed that they follow the previously verified pattern, with the majority of authors using regression techniques. In addition to the OLS and Logit models, we highlight the use of Poisson regression models, used in three studies (De Freitas, 2022; De Groote; Pepermans; Verboven, 2016; Min; Lee; Hurvitz, 2023). According to the authors, Poisson regression is the most appropriate model to use with countable dependent variables, such as the number of PV systems per census tract. Additionally, when there are a large number of zeros in the dependent variable data, it is appropriate to use a Poisson Pseudo Maximum Likelihood estimator (De Freitas, 2022) or zero-inflated negative binomial regression models (Kwan, 2012).

Regarding the methods used to assess the regressive effect of the incentive policies for DGPV, as illustrated in Table 2, mainly electricity market models were used. It should be noted that, in general, they are not commercial models used to simulate the operation of power systems, but a series of empirical equations developed by the authors to reproduce the effects of subsidies on tariffs and their impacts on the household budget, usually on an annual basis (Frondel; Sommer; Vance, 2015; Grösche; Schröder, 2014; Nelson; Simshauser; Kelley, 2011; Nelson; Simshauser; Nelson, 2012; Strielkowski et al., 2019; Strielkowski; Štreimikienė; Bilan, 2017). McConnell et al. (McConnell et al., 2013), on the other hand, developed a five-minute dispatch model to reproduce the operation of the Australian National Electricity Market with the insertion of DGPV and verify the effect on the electricity spot price.

Table 2 - Methods used to evaluate whether DGPV incentive policies have regressive economic effects

Method	No. of Papers
Electricity Market Model	8
Regression	3
General Equilibrium Model	2
Inequality Metrics	2
Simulation	2
Distribution Charts	1

Note: The sum is greater than the number of articles due to the use of multiple methods in some articles.

It is also worth mentioning the use of models that are based on the General Equilibrium theory (input-output models and computable general equilibrium models). These are models that represent the economy of a given region by sectors and simulate the behavior of supply, demand and prices to keep the economy in balance. These models allow evaluating indirect effects of public policies, such as FiT. To illustrate, the implementation of FiT policies may incur costs that result in an elevation of overall electricity tariffs. This adjusted price can influence how businesses consume electricity and manage their production processes. Consequently, companies may opt to raise the prices of goods due to the increased costs, thereby impacting consumers indirectly. Conversely, businesses in the renewable energy sector may experience growth, leading to the creation of new jobs and income. Hence, models based on General Equilibrium assist in comprehending the ramifications of energy policies by taking into account intricate interactions among diverse sectors and agents. Böhringer et al. (2017), for example, use a computable general equilibrium model (CGE) together with microsimulation to be able to assess the overall effect of the FiT on the German economy while having a detailed perspective of the effect on households.

However, a critique can be leveled at the omission of indirect electric effects of PV in these models. Costs associated with energy losses and the necessity for new investments in the distribution and transmission grid, for example, were not evaluated in the reviewed studies, which implies that the results might be incomplete.

2.3.2 Is there inequality in the uptake of residential grid-connected PV systems?

2.3.2.1 Income and wealth inequality

In this section, 74 articles that evaluated the issue of inequality in the adoption of rooftop solar were analyzed. We found that residential PV installations or subsidies for this technology are distributed unevenly according to income in 43 articles (Alderete Peralta; Balta-Ozkan; Longhurst, 2022; Andor; Frondel; Vance, 2015; Araújo; Boucher; Aphale, 2019; Bao et al., 2020; Bennett et al., 2020; Bernards; Morren; Slootweg, 2018; Best; Chareunsy; Taylor, 2023a, 2023b; Borenstein, 2017; Borenstein; Davis, 2016; Darghouth et al., 2022; De Freitas, 2022; De Groote; Pepermans; Verboven, 2016; Dharshing, 2017; Etongo; Naidu, 2022; Feger; Pavanini; Radulescu, 2022; Griffith; Higgins; Turner, 2014; Grösche; Schröder, 2014; Grover; Daniels, 2017; Hansen; Jacobsen; Gram-Hanssen, 2022; Kim et al., 2023; Kwan, 2012; Lekavičius et al., 2020; Nelson; Simshauser; Nelson, 2012; O’Shaughnessy; Kim; Darghouth, 2023; Poruschi; Ambrey, 2016, 2019; Reames, 2020; Ros; Sai, 2023a; Ruokamo et al., 2023; Schaffer; Brun, 2015; Shittu; Weigelt, 2022; Sigrin; Pless; Drury, 2015; Stewart, 2022; Thompson et al., 2021; Vaishnav; Horner; Azevedo, 2017; Varela-Margolles; Onsted, 2014; Vasseur; Kemp, 2015; Wang et al., 2022; Wicki; Pietrzykowski; Kusz, 2022; Winter; Schlesewsky, 2019; Yu et al., 2018; Zhang; Ballas; Liu, 2023). These studies show, especially through descriptive statistics (such as distribution charts) or regression methods, that adoption is associated with higher levels of income. Other studies did not use the income variable, but also found an inequality based on alternative economic metrics, such as socioeconomic indexes (Costa; Santos, 2020; Fournier et al., 2020; Lukanov; Krieger, 2019; Macintosh; Wilkinson, 2011), building characteristics such as size and constructive quality (Best, 2022b; Jayaweera;

Jayasinghe; Weerasinghe, 2018), home value (Best; Esplin, 2023; Kraaijvanger et al., 2023), financial inclusion index (Aarakit et al., 2022), and wealth (Best, 2022a; Best; Burke; Nishitateno, 2019; Best; Chareunsy; Li, 2021; Best; Nepal; Saba, 2021).

In relation to wealth, it is worth mentioning that this metric is defended by some authors (Best; Burke; Nishitateno, 2019; Best; Chareunsy; Taylor, 2023a, 2023b; Best; Nepal; Saba, 2021) as being more important than income to explain the adoption of DGPV. In fact, these studies found a less or insignificant effect of income when accounting for wealth. Due to the high initial cost of photovoltaic systems, it is understood that having savings is important for investing in this technology. Even if wealth is in the form of illiquid assets, such as housing assets, still there are benefits, since people tend to spend and invest more when perceiving themselves wealthier. Finally, greater wealth also facilitates access to financing (Best; Nepal; Saba, 2021). It is noteworthy that the net worth of tenants was also observed as a statistically significant variable to explain the PV adoption in rented households (Best, 2022a; Best; Chareunsy; Taylor, 2023b).

Two articles explored possible differences in the results according to the level of data disaggregation (Best; Chareunsy, 2022; Tidemann et al., 2019). The authors found in studies with aggregated data (statistical area or zip code) an inverse relationship between income (or socioeconomic index) and the adoption of residential PV systems. That is, the higher the income, the lower the adoption. However, when the studies were performed with more granular data (household or mesh block), a positive relationship was found, as in previous studies. A comparable outcome was identified by Behnke and Shelton (2024), wherein a preliminary analysis revealed an increase in PV adoption within low-income and predominantly Black-populated postcodes in Atlanta, Georgia (US). However, upon a closer examination of property-level characteristics, the authors discerned that the elevated adoption rates were propelled by middle and upper-class newcomers in the neighborhoods during a gentrification process in the city.

Seven articles found a negative relationship between income (or socioeconomic index) and the adoption of PV systems. However, these studies have some caveats. Stewart (2021) showed that FiT payments were predominantly directed towards underserved areas through community solar systems. However, when analyzing the adoption of own residential systems, the author found an opposite result, namely, allocation of subsidies predominantly for high-income areas. Copiello and Grillenzoni (2021) concluded that in Italy there was an inverse relationship between per capita income and installed PV capacity. However, the study was conducted with aggregated data (municipal level), which may influence the result, as previously stated. Similar critiques can be applied to the studies conducted by Olczak et al. (2021), Palm (2020), Simpson and Clifton (2017), and Zhang et al. (2023), all of which identified a negative relationship, albeit at aggregate levels. Irfan et al. (2021) analyzed adoption in India and concluded that an increase in household income tends to decrease the likelihood of adoption of PV technology compared to other microgeneration technologies. However, the authors comment that India has an unreliable electricity supply, with frequent supply cuts. Therefore, it is natural for households to have a backup system, and the wealthiest families prefer to use other technologies, such as gasoline motor generators.

Finally, six studies did not identify statistically significant results regarding the effect of income or other economic variables on the adoption of residential PV systems (Balta-Ozkan; Yildirim; Connor, 2015; Graziano; Gillingham, 2015; Keady et al., 2021; Lan; Gou; Lu, 2021; Min; Lee, 2023; Min; Lee; Hurvitz, 2023).

Based on the papers presented in this section, it has become evident that there is strong evidence of unequal uptake of rooftop solar across different socioeconomic groups. While lower income and wealth inhibit investments in solar energy by lower-income households per se, we can discuss other characteristics that also explain the lower adoption within this group. Various authors have delved into this topic and found that difficulties in accessing financing, housing-related structural aspects, lack of information, language barriers (Heeter et al., 2021), lower rates of home ownership (Darghouth et al., 2022) and challenges in benefiting from subsidies in the form of tax credits (Borenstein; Davis, 2016) are among the additional reasons. From an electrical perspective, Hartvigsson et al. (2023) found that hosting capacity is not equally distributed, and it is less available for households with a higher socioeconomic burden. Lastly, on the supply side, it has been observed that distributed generation installers are typically situated in more affluent areas, resulting in fewer proposals being sent to households in less affluent areas and to customers interested in renting solar systems (O'Shaughnessy et al., 2021).

Table 3 – Summary of studies according to the relationship found between PV adoption and income/wealth

Relationship	References
Positive	Bao et al. (2020), Thompson et al. (2021), Varela-Margolles and Onsted (2014), Etongo and Naidu (2022), Ruokamo et al. (2023), Vasseur and Kemp (2015), Yu et al. (2018), Costa and Santos (2020), Fournier et al. (2020), Grösche and Schröder (2014), Lukanov and Krieger (2019), Griffith et al. (2014), Reames (2020), Sigrin et al. (2015), De Groote et al. (2016), de Freitas (2022), Kwan (2012), Nelson et al. (2011), Araújo et al. (2019), Shittu and Weigelt (2022), Schaffer and Brun (2015), Darghouth et al. (2022), Bennett et al. (2020), Bernards et al. (2018), Lekavičius et al. (2020), Wicki et al. (2022), Andor et al. (2015), Poruschi and Ambrey (2016), Grover and Daniels (2017), Alderete Peralta et al. (2022), Borenstein and Davis (2016), Winter and Schlesewsky (2019), Feger et al. (2022), Dharshing (2017), Hansen et al. (2022), Stewart (2022), Borenstein (2017), Vaishnav et al. (2017), Best et al. (2023a), Best et al. (2023b), Zhang et al. (2023), O'Shaughnessy et al. (2023), Kim et al. (2023), Ros and Sai (2023a) Wang et al. (2022), Macintosh and Wilkinson (2011), Best (2022b), Jayaweera et al. (2018), Best and Esplin (2023), Kraaijvanger et al. (2023), Aarakit et al. (2022), Best et al. (2021), Best (2022a), Best et al. (2019), Best et al. (2021), Tidemann et al. (2019), Best and Chareunsy (2022), Stewart (2021)
No relationship	Keady et al. (2021), Min et al. (2023), Min and Lee (2023), Lan et al. (2021), Graziano and Gillingham (2015), Balta-Ozkan et al. (2015)
Negative	Simpson and Clifton (2017), Stewart (2021), Copiello and Grillenzoni (2021), Olczak et al. (2021) Palm (2020), Zhang et al. (2023), Irfan et al. (2021)

2.3.3 How the inequality evolved over time?

In this section, we seek to answer whether the previously identified unequal adoption is reduced over time. To do that, 17 articles that explored this issue were analyzed.

First, some studies have not found differences over time. Sigrin et al. (2015) evaluated the diffusion between early adopters (2007 – 2010) and more recent adopters (2011 – 2013) in San Diego County (USA), but did not find a statistically significant difference in income. A weak difference was found between two periods (up to 2012 and between 2013 and 2015) in Denmark (2022). In Australia, three studies assessed the effect of wealth on the adoption of PV systems between two close periods (two to three years) and found similar effects on both dates (Best, 2022a; Best; Burke; Nishitateno, 2019; Best; Chareunsy; Li, 2021). In a study that covers a longer period (2012-2020), Best et al. (2023a) found that there is persistent inequality for the lowest net-wealth decile; however, improvements for deciles three to five have been evident. Finally, in a study encompassing Brazil, Chile and Mexico, Chueca et al. (2023) found inconclusive effects of income in the adoption over time; however, the analysis is at municipal level.

Next, a few studies found that the inequality worsened in some cases. In Australia, Macintosh and Wilkinson (2011) evaluated the distribution of subsidies between 2000 and 2010 of the Photovoltaic Rebate Program. According to the authors, at the beginning of the program, the subsidies reached a greater portion of households located in postal codes of low and medium-low Socioeconomic Status (SES). However, in the last period analyzed, only 11% of beneficiaries were from low SES areas. Therefore, according to the authors, there was a worsening in the distribution of subsidies in this program. Also in Australia, Best et al. (2023b) studied adoption patterns between 2012-2020 for renters, and found inequality has emerged and is widening over time. Finally, Stewart (2022) evaluated the Scottish case between 2009 and 2020 and found that the gap in DGPV diffusion among socioeconomic groups continues to grow. In this study, the author identified that the neighborhood effect is one of the reasons for maintaining the inequality. That is, initial adoption in wealthier households stimulates diffusion in higher-income clusters.

On the other hand, some studies found an improvement in the adoption inequality. In the USA, O'Shaughnessy et al. (2023) show that the PV adoption share by low- and moderate income households (below median income) grew from about 8% in 1990 to 18% in 2020. Despite the improvement, the group remains about 32 points under-represented among PV adopters. Borenstein (2017) assessed the income of solar adopters between 2007 and 2014 and concluded that the distribution remains strongly inclined towards the wealthiest, although inequality has declined since 2011. Lukanov and Krieger (2019) found a similar result, when analyzing the adoption of PV per capita in census tracts in California. Although insertion has increased in recent years of analysis in disadvantaged communities, the gap continues to grow relative to the best-status groups (albeit at a slower rate). With respect to the distribution of subsidies (rebates, grants and federal investment tax credits), Vaishnav et al. (2017) identified that between 2006 and 2014 there was a reduction in inequality, although it still existed at the end of the analysis period. In Brazil, between 2013 and 2019, it was found that the average income of the census tract continues to have a positive relationship with the adoption of DGPV. However, the magnitude of elasticity decreases between the beginning and end of the analysis (De Freitas, 2022). De Groote et al. (2016) when analyzing the determinants for the adoption of DGPV in households in Flanders (Belgium), found a significant association between adoption and income only in the first period (2006 - 2009). Subsequently, between 2010 and 2012, the impact of income was not statistically significant.

One pertinent discussion in this section can be drawn from the work of O'Shaughnessy et al. (2023), who projected that by 2030, due to the technology diffusion process of PV in the USA, the share of low- and moderate-income (LMI) PV adoption will be comparable to other technologies at similar penetration levels. Conversely, the study by Wang et al. (2022) indicate that low-income communities are not only delayed in their initial adoption of PV but also tend to reach saturation more quickly at lower levels of adoption. It's worth noting that the first study includes moderate-income households, while the latter focuses solely on low-income households. In fact, Best et al. (2023a) found in Australia that, despite improvements for deciles three to five, persistent inequality remains for the lowest net-wealth decile. Hence, we argue that the assessment of distributional justice should be conducted in a more granular manner to capture the evolution of inequality, particularly among more vulnerable groups, such as those in the first income decile.

A summary of results for this section is presented in Table 4.

Table 4 – Summary of studies according to the income/wealth inequality evolution in PV adoption

Inequality Evolution	References
Inequality increase	Stewart (2022), Best et al. (2023b), Macintosh and Wilkinson (2011)
No difference	Sigrin et al. (2015), Hansen et al. (2022), Best et al. (2023a), Best et al. (2021), Best (2022a), Best et al. (2019), Chueca et al. (2023)
Inequality decrease	Lukanov and Krieger (2019), De Groote et al. (2016), de Freitas (2022), Borenstein (2017), Vaishnav et al. (2017), O'Shaughnessy et al. (2023)

2.3.4 Regressive impacts of DGPV incentive policies

As previously shown, the adoption of DGPV occurs, in general, in an unequal way, with a concentration on higher-income households. This section discusses whether DGPV penetration had regressive economic impacts on households. That is, if incentive policies to DGPV resulted in a disproportionate cost to the have-nots of society.

In New South Wales, Australia, Nelson et al. (2011) found that FiT are highly regressive, which implied a taxation rate 2.6 times higher for households in the lowest income bracket compared to higher-income households. A similar study by the same authors for the state of Queensland found that the effective rate of taxation paid by low-income households is 3.4 times higher than that of high-income households (Nelson; Simshauser; Nelson, 2012). In contrast to the previous study, McConnell et al. (2013) argue that FiT costs are offset by a reduction in spot electricity prices with the insertion of DGPV. With a lower demand for electricity, there would be the dispatch of cheaper generation plants, which would benefit all consumers. This is known as the "merit order effect". However, Nelson et al. (2012) argue that this effect is transitory. According to the authors, the reduction in spot prices leads to fewer investments and consequently higher prices in the future. Therefore, the result would continue to be adverse from a distributive point of view.

In the United Kingdom, three studies reached similar conclusions, that the adoption of DGPV seems to be subsidized by lower-income households, with a transfer of costs and wealth (Farrell, 2021; Strielkowski et al., 2019; Strielkowski; Štreimikienė; Bilan, 2017). The authors argue that households with DGPV do not contribute to the grid costs as they should. Thus, the reduction in revenue needs to be compensated with tariff increases.

In Germany, six studies have analyzed the effect of the Erneuerbare-Energien-Gesetz (EEG) policy, which focuses on paying FiT for specific technologies. The cost of this policy is passed on to consumers through an additional charge on the electricity bill. However, residential consumers pay a fee about 100 times higher than industrial consumers. Thus, the positive benefit of the merit order effect is absorbed mainly by industrial consumers, while costs fall on households (Cludius et al., 2014). Looking specifically at the effect in households, since the rate is practically uniform (in $/kWh) between households, it has a regressive impact, which means an effect of 1.0 to 2.4% on different income inequality metrics (Winter; Schlesewsky, 2019). Böhringer et al. (2017) found a similar impact of 1.3% on the Atkinson index. Due to the concentration of DGPV systems in higher-income households, there is a capture of subsidies by the wealthy, while the costs especially impact lower-income households (Grösche; Schröder, 2014). According to Frondel et al. (2015) in 2012, households below the poverty line spent 0.75% of their income on renewables, while the wealthiest spent only 0.2%. A similar result was found by Többen (2017), who concluded that "while the majority of income brackets experience positive total net impacts, it can be observed that households below the national median income predominantly lose shares in the total disposable of their states" due to the EEG.

Previous work covers a common theme of the evaluation of FiT policies. Regarding the net-metering scheme, we identified studies that assess the existence of cross-subsidies and their effect on tariffs, such as Kubli (2018), but that do not explore their distributive effects between different income groups.

A summary of results for this section is presented in Table 5.

Table 5 – Summary of studies according to characteristics of incentive policies to rooftop PV

Economic Impact	References
Regressive	Nelson et al. (2012), Nelson et al. (2011), Strielkowski et al. (2019), Strielkowski et al. (2017), Böhringer et al. (2017), Andor et al. (2015), Farrell (2021), Cludius et al. (2014), Többen (2017)
Progressive	McConnell et al. (2013)

2.3.5 Recommendations

2.3.5.1 Recommendations to reduce DGPV inequality

A series of studies recommended improving the targeting of subsidies to the poorest households (Bennett et al., 2020; Best, 2022a; Best; Chareunsy, 2022; Best; Chareunsy; Li, 2021; Best; Nepal; Saba, 2021; Chueca et al., 2023; Dharshing, 2017; Fournier et al., 2020; Griffith; Higgins; Turner, 2014; Keady et al., 2021; Kraaijvanger et al., 2023; Lekavičius et al., 2020; O'Shaughnessy, 2022; Simpson; Clifton, 2017; Stewart, 2022; Wang et al., 2022). In general, these studies focus on an income criterion to be eligible for the incentive program, or on the gradual granting of benefits, which decreases as income increases. On the other hand, some studies focusing on Australia and the USA argue that reducing inequality would be more effective if resources were directed according to the level of wealth, not income (Best; Esplin, 2023; Best, 2022a, 2022b; Best; Chareunsy, 2022; Best; Chareunsy; Li, 2021; Best; Chareunsy; Taylor, 2023a, 2023b; Best; Nepal; Saba, 2021). In this sense, an asset that could be used as an eligibility criterion is the balance in private pension accounts, given its high positive relationship with the adoption of DGPV systems (Best; Nepal; Saba, 2021). Other authors (Best, 2022a, 2022b; Min; Lee; Hurvitz, 2023; Stewart, 2022) suggest that, in addition to wealth, the allocation of incentives to rented homes and public or multi-family housing should be prioritized, as these are groups with low adoption.

Given the barrier related to the high cost of DGPV systems, some authors advocate the creation of a subsidy to reduce the initial investment (Best; Burke; Nishitateno, 2019; Jayaweera; Jayasinghe; Weerasinghe, 2018), such as rebates. However, Best et al. (2021) recommend that the payment be unlinked to the size of the system, as there is no evidence that larger subsidies affect the decision of the installed power. In this regard, it's worth mentioning an innovative and equitable reverse auction mechanism proposed by Best (2023). The author suggests that conducting sub-auctions based on socioeconomic groups could harness the cost-effective nature of reverse auctions while aiming for greater equality among various socioeconomic segments. However, it's essential to note that this mechanism has not been implemented to date, and there are practical concerns regarding its application.

Subsidized loans and the stimulus of the solar leasing model can also be mentioned as alternatives to overcome the barrier of high equipment costs (Best; Burke; Nishitateno, 2019; Darghouth et al., 2022; Griffith; Higgins; Turner, 2014; Lekavičius et al., 2020). However, Darghouth et al. (2022) found that smaller companies usually install PV systems in low-income households and have difficulty offering more complex business models, such as leasing. Therefore, the authors recommend that policymakers explore ways to facilitate leasing, such as through public green banks, to enable the offer of this business model by smaller companies. Another way to subsidize the initial investment is through tax credits. However, Borenstein and Davis (2016) discussed that the nonrefundable tax credit model used in the USA tends to favor higher-income households, because most low-income households have a nonpositive tax liability.

Among the recommendations of incentive programs, some authors recommend facilitating community solar plants (Best; Chareunsy; Taylor, 2023a; Darghouth et al., 2022; Graziano; Gillingham, 2015; Lekavičius et al., 2020; Lukanov; Krieger, 2019; Stewart, 2021; Vaishnav; Horner; Azevedo, 2017), which are projects that generate energy for more than one consumer. Through these projects, the user can buy or rent part of the power plant, and the benefits are credited to their electricity bill, even though the generation is far from consumption. With this, even those consumers who do not have a roof available can also have access to solar energy. Similarly, those who rent the property can also join a community generation program because, in case of change of address, it is possible to transfer the credits to the new address. In fact, Darghouth et al. (2022) found that the low rate of home ownership among low-income households is one of the barriers to greater adoption of DGPV in the most vulnerable groups. Therefore, community generation programs are considered appropriate to increase adoption in lower-income households.

In fact, incentive programs aimed at low- or moderate-income households (LMI) have been shown to be effective in reducing the inequality of access to DGPV. An evaluation of programs to this end in the state of California and Connecticut showed that incentives were responsible for adoption in LMI households in 80% of cases (O'Shaughnessy, 2022). This study evaluated the California Single-Family Affordable Solar Homes program, which subsidizes part of the initial investment, and the Connecticut Solar for All Program, which offers subsidized leasing for PV systems. Gao and Zhou (2022) also found that inclusion policies in the adoption of DGPV were successful in the United States, especially in low-income households in Asian-

, Hispanic-, or White-majority sectors. However, the policies did not have a statistically significant result in Black-majority sectors. Therefore, the authors suggest customizing solar justice policies to specifically target the Black population.

However, the existence of incentive programs aimed at vulnerable households must be accompanied by educational outreach and public engagement campaigns to increase public awareness of solar benefits and the availability of incentive programs (Gao; Zhou, 2022; Jayaweera; Jayasinghe; Weerasinghe, 2018; Reames, 2020; Shittu; Weigelt, 2022; Stewart, 2021, 2022; Thompson et al., 2021; Varela-Margolles; Onsted, 2014). Shittu et al. (2022), for example, identified that in the United States, incentive programs focused on low-income households are more widely disseminated by utilities with wealthier customers. That is, access to those programs must be better communicated where there is a greater need. Furthermore, Varela-Margolles and Onsted (2014) argue that in addition to improving communication, incentive programs should have minimal red tape. Jayaweera et al. (2018) found a positive relationship between higher education and the adoption of DGPV systems in Sri Lanka. In this sense, as a long-term strategy, they recommend increasing opportunities for higher education to accelerate the diffusion of innovations.

Finally, it is worth discussing the perspective introduced by O'Shaughnessy et al. (2023). They posit that the primary catalyst for enhancing adoption equity lies within the broader technological diffusion process. Consequently, to achieve a fairer outcome, policies should not exclusively focus on low-income households but should encourage the widespread deployment of PV systems. While it's acknowledged that in the short term, income-agnostic policies may have regressive consequences, they could set the stage for mass adoption and cost reductions, ultimately making solar energy more accessible for low-income households.

2.3.5.2 Recommendations to reduce regressive effects of incentive policies

Another series of studies focused on reducing the regressive effects of subsidies through changes in the design of the programs. Grover and Daniels (2017) argue that in the UK the distribution of policy costs should be adjusted, charging households proportionally to their consumption or income. In the German case, Frondel et al. (2015) advocate a means-tested cash transfer to poor households to compensate them for increases in electricity costs. The authors also advocate that the FiT model should be abolished and replaced by a more efficient model such as a renewable energy quota system combined with green energy certificates. Böhringer et al. (2022; 2017) posit that three alternative funding mechanisms could be instituted for renewable energy projects, mitigating the regressive effects of tariff surcharges. These alternatives include: (i) exempting households from FiT surcharges, thereby placing the burden solely on the industry; (ii) substituting the tariff surcharge with an elevation in mineral oil taxes; or (iii) implementing an increase in value-added taxes. Notably, all three financing options demonstrate a progressive impact, leading to decreased electricity prices for households.

Another group of studies makes recommendations related to the tariff structure to reduce the regressive effects of DGPV penetration. Strielkowski et al. (2017), for example, recommend the creation of new forms of charging for the use of the electricity grid, because volumetric tariffs ($/kWh) cannot recover the cost as the adoption of DGPV increases. Thus, they suggest the use of multipart electricity tariffs, with a fixed part, a maximum demand portion ($/kW peak), and a variable part ($/kWh). Another option suggested by the authors is a tariff on the maximum power exported to the network ($/kW peak). The multipart tariff model is also advocated by Farrell (2021) as a way to avoid loss of welfare with the adoption of DGPV and its redistribution from non-adopters to adopters. The author explains that changing a volumetric tariff to a multipart tariff has the potential to cause regressive effects to more vulnerable consumers, but maintaining volumetric tariffs generates a much greater loss of welfare. Thus, the author argues that it is more efficient to migrate to the multipart tariff and contain its negative effects through a specific discount for vulnerable consumers. Additionally, a fixed charge on electricity taxes is advocated to reduce cross-subsidies (Gunkel et al., 2023).

On the other hand, Feger et al. (2022) in a study for the canton of Bern, Switzerland, found that increasing the value of volumetric tariffs ($/kWh) would be the most cost-effective and progressive way to encourage the adoption of DGPV. This measure causes the regressive effect reported by Strielkowski et al. (2017) but causes a higher progressive effect due to the greater contribution to the use of the grid by non-adopter rich households. This result was maintained even in a simulation of the "death spiral", in which the dynamics of adoption of DGPV and its impact on tariffs over 10 years were considered. However, it should be noted that the measure of increase in volumetric tariffs as a way of encouraging the adoption of DGPV causes an aggregated welfare loss, which is aligned with Farrell's conclusions (Farrell, 2021) in relation to the use of volumetric tariffs. In another study, Vaishnav et al. (2017) argue that compensation for energy injected into the grid by distributed generators should match more closely the value of electricity at a particular time and place. For this, it is recommended to apply dynamic tariffs that reflect the marginal cost of generation and externalities. A comparable conclusion was reached by Khan et al. (2023), who assert that hourly locational tariffs represent the most equitable tariff structure.

Finally, in accordance with the energy justice framework proposed by Sovacool et al. (2016), the decision-making process involving agenda setting, formulation, implementation, and evaluation of these recommendations must ensure meaningful involvement and access for all segments of society.

2.4 Future research agenda

In this section, we present a set of recommendations for future studies that can build upon the findings and insights of this research.

a) Greater geographic diversity: Only 9% of the studies reviewed were concentrated on developing countries. Considering the higher inequality indexes in developing countries (Makhlouf, 2023), potential adverse effects of PV adoption could be even more relevant. While acknowledging that our research design, which excluded studies focusing on off-grid and rural applications, may have influenced this low participation, we contend that a considerable portion of solar adoption in developing countries lacks examination through distributive lenses. This assertion is grounded in the fact that the majority of distributed generation capacity installed worldwide, even in developing countries, is presently connected to the grid (IEA PVPS, 2022). Furthermore, around 75% of the studies in our review are concentrated in only four countries (United States, Australia, Germany, and United Kingdom). The dynamics of PV adoption in these four nations may differ from those in other countries. Thus, there is an opportunity for future research to delve into this less represented group of countries. Additionally, conducting studies that encompass multiple countries within a single paper could allow for comparisons of inequality across various contexts.

b) Closer look to racial inequality: The examination of racial inequality in PV adoption represents an emerging field within the literature, which we did not address in this review. Indeed, race stands out as one of the less researched predictors of PV adoption, with divergent findings in the existing literature (Alipour et al., 2020). Therefore, the racial theme could be further explored in future studies to provide more assertive information to policymakers.

c) More and comprehensive distributive impact assessment models: As indicated in Table 5, it is evident that a smaller number of articles delved into the distributional impact of DGPV policies compared to those focusing on the inequality in adoption. Moreover, it was found that impact studies were based primarily on electricity market models or general equilibrium models, which have limitations to fully represent the effects of DGPV adoption in power systems and, consequently, tariffs. The effect of electrical losses, investments in transmission and distribution networks, for example, were little explored by the literature analyzed. While acknowledging the existence of a significant body of literature on impact assessments of distributed PV that considers these indirect effects, it is noteworthy that only a limited subset of this literature also addresses the distributional aspect of impacts.

d) Distributive impact under different incentive mechanisms: most of the reviewed studies have focused on the distributive effects of feed-in tariffs. Despite the presence of impact assessments in the literature for alternative mechanisms, such as net-metering or net-billing schemes, we did not encounter articles that conducted a distributional analysis of their impacts. Consequently, there exists a potential avenue for future research to investigate the distributive impacts under different incentive mechanisms.

e) Evaluation of policies targeting low-income households: in recent years, several initiatives have been implemented to address the inequality problem in the adoption of grid-connected rooftop solar. While there are existing studies in specific contexts (Gao; Zhou, 2022; O'Shaughnessy, 2022), there is an opportunity to broaden the research to encompass additional contexts and evaluate the causality of these programs on inequality metrics and their efficiencies compared to other measures.

f) Striking the right balance between targeting incentives to low-income households and providing general incentives: Policies designed to foster the diffusion of technologies can lead to cost reductions, potentially mitigating inequality in adoption. Conversely, tailoring subsidies to individual needs can provide immediate assistance to those in particular need. The challenge lies in finding the optimal balance between these two types of incentives to achieve the most effective outcome.

g) Emphasizing the evolution of income distribution over time: While many studies have identified a positive relationship between income and solar adoption, there has been less emphasis on examining how PV adoption evolves across income groups.

A more thorough investigation of this aspect is crucial for informing the development of more effective policies.

2.5 Conclusions

This essay sought to explore the aspect of distributional justice in the adoption of grid-connected residential PV (DGPV) around the world. This technology is transforming electrical systems and allowing consumers to play an active role in power generation. Additionally, the adoption of DGPV brings several benefits, such as reducing the cost of electricity, protecting against future increases in electricity tariffs and increasing the value of the home. However, it is important that this transformation is also inclusive, which means that these benefits can be harvested by all, and that the costs of incentive programs do not burden the most vulnerable population segments. In this sense, a systematic review was conducted that resulted in a list of 87 studies related to the subject.

In terms of studies characteristics, it was possible to see that most of the studies examined the situation in developed countries, with only 9 percent of research encompassing developing economies. In methodological terms, most of the studies explored the relationship between income and the adoption of DGPV systems through regression models. Another widely used method was the elaboration of frequency charts, usually with the number of systems installed per quantile or income bracket. The results of some of these studies suggested the importance of performing evaluations at the lowest level of disaggregation, namely the household level, because some studies found different results when performing the same analysis at the aggregate level.

According to the literature, there is substantial evidence that there is inequality in the adoption of DGPV systems and in the distribution of subsidies to promote the deployment of distributed solar energy. In general, there is a concentration of DGPV systems in households with higher income, higher wealth, or better socioeconomic indices. On a positive note, most studies that have evaluated the effects of inequality over time reveal a reduction in the concentration of DGPV systems. However, despite the improvements, DGPV adoption remains largely concentrated among the wealthiest households.

It was also evident that policies to promote the adoption of DGPV, especially FiT, have regressive characteristics. In other words, the costs of subsidies are usually passed on to electricity tariffs and impact disproportionately lower-income households, which generally commit more of their budget to electricity payments. Moreover, the concentration of DGPV systems in higher-income households means that they receive the majority of these subsidies, while the burden is shouldered by non-adopters. This problem is aggravated by the use of volumetric tariffs, which are no longer paid by the DGPV adopters. Therefore, it must be increased to recover the fixed costs of the electrical system.

In terms of recommendations, most of the studies understand that there should be a targeting of subsidies to the most vulnerable households, using criteria of income, wealth, and that favor public and rented housing. Additionally, the use of mechanisms that reduce the initial investment barrier, such as through cash rebates, subsidized financing, or leasing is recommended. The use of community solar facilities was also highly recommended, as an alternative to adoption for rented households or those without a roof available. However, the targeting of programs to vulnerable households must be accompanied by educational outreach and public engagement campaigns to increase public awareness of solar benefits and the availability of incentive programs.

Regarding the regressive effects of subsidies, the authors recommend that the costs of the programs be charged differently. To mitigate the financial burden on low-income households, they recommend adjusting the recovery of subsidy costs to be proportional to household consumption or income. An alternative approach involves transferring the surcharges from the electricity bill and recovering the costs through the tax system, potentially by increasing the Value-added Tax (VAT) or the tax on mineral oil. These financing alternatives exhibit a progressive effect by reducing electricity prices, particularly benefiting low-income households that allocate a higher proportion of their income to electricity expenses. However, it is also suggested to exchange the FiT incentive model for market-oriented models, such as a renewable energy quota program combined with green energy certificates. Moreover, it is necessary to review the design of electricity tariffs to avoid cross-subsidies and the loss of welfare. Multipart tariffs with fixed and variable components aligned with the costs of the electricity sector are indicated in this context of increased share of distributed energy resources.

While a systematic review was employed to mitigate selection bias and enhance the reliability of our findings, it is crucial to acknowledge and address inherent limitations in the scope and methodology of this study. Firstly, the analysis predominantly focused on economic inequality, excluding other dimensions of energy injustice. Secondly, the study's conclusions are confined to grid-connected systems, omitting considerations of off-grid and rural incentive policies, potentially introducing a geographical bias towards developed countries. The data collection and analysis were executed by a single author, potentially introducing bias, although adherence to the PRISMA framework was maintained to mitigate this concern. Lastly, the review lacks a weighting mechanism for assessed articles based on their methodological rigor, although individual study limitations are addressed when pertinent to the conclusions.

Despite the limitations, this review reveals that the uptake of grid-connected residential PV systems exhibits persistent distributional injustices in our society. The adoption of DGPV systems has been concentrated in households with better socioeconomic status, even after decades of development. Some programs focusing on low-income households were successful in increasing adoption within this group, although with limited and localized results. This concentration, associated with a poor design of incentive policies and electricity tariffs, results in regressive economic effects, putting pressure on the budget of the most vulnerable families. In addition to adverse economic effects and ethical reasons, the distancing of a considerable group of consumers from photovoltaic technology can undermine the ambitions of decarbonization of the power sector across the world. Therefore, there is a need to redesign policies and tariffs so that the energy transition happens more fairly.

3 SECOND ESSAY: SHINING A LIGHT ON DISPARITIES: A COMPARATIVE ANALYSIS OF RESIDENTIAL PHOTOVOLTAIC ADOPTION INEQUALITY IN AUSTRALIA AND BRAZIL

ABSTRACT

There is a growing consensus that the energy transition must also be just. In this context, the inequality in the adoption of residential photovoltaic (PV) systems is under scrutiny as solar energy adoption rises. Despite the existing evidence of the inequality in PV adoption, there is a need to examine how this issue has evolved across different contexts, particularly in developing countries. This paper aims to compare the inequality in PV adoption between Australia and Brazil over the last decade. The mix of methods includes analyzing descriptive statistics, a Solar Gini index, and regression models. The findings reveal that inequality in residential PV adoption in both countries has not changed substantially. Lower-income quintiles have faced lower adoption probabilities than higher-income groups. However, Australia demonstrates a better position, with a more equitable distribution of solar systems across income groups. The lack of inequality change suggests that technology diffusion alone may not eliminate PV access inequality for low-income groups. It emphasizes the ongoing need for targeted policies to enhance justice in solar access.

Keywords: Energy justice; Inequality; Solar Energy; Distributed generation; Gini.

3.1 Introduction

Energy justice is a cross-cutting field of research that has been gaining popularity over the last decade aiming to have justice permeating the energy sector (Heffron, 2022). This surge aligns with intense efforts to address climate change through a transition to low-carbon practices, which can, in turn, accentuate inequalities in various energy activities (Carley; Konisky, 2020). The adoption of grid-connected residential photovoltaic (PV) systems, for instance, has become a focal point in discussions on demographic inequality, with income and

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Abbreviations: ABS, Australian Bureau of Statistics; FiT, Feed-in Tariff; GNI, Gross national income; ICMS, Tax on the movement of goods and services; IBGE, Brazilian Institute of Geography and Statistics; IEA, International Energy Agency; LPM, Linear Probability Model; LRET, Large-Scale Renewable Energy Target; PNAD-C, Continuous National Household Sample Survey; PV, Photovoltaic; PVRP, Photovoltaic Rebate Program; RET, Renewable Energy Target; SIH, Survey of Income and Housing; SHCP, Solar Homes and Communities Program; SRES, Small-scale Renewable Energy Scheme.

wealth significantly influencing the diffusion of this technology (Konzen; Best; De Castro, 2024; Sovacool et al., 2022). Examining the deployment of solar energy through the lens of the energy justice framework is particularly relevant due to the foreseen diffusion of distributed solar systems in the coming years. The International Energy Agency, in its Net Zero Emissions by 2050 scenario, envisions a global total of 100 million households equipped with PV by 2030. This means a fourfold increase in residential rooftop solar systems compared to 2022 figures (IEA, 2022).

In this context, it is essential to underscore why addressing the inequality in the adoption of residential PV systems is important. As highlighted by Bidwell and Sovacool (2023), one perspective asserts that justice is an intrinsic value rooted in egalitarian ethics and democratic principles. Thus, the pursuit of an equitable distribution of solar systems is deemed ethical. Another perspective views energy justice as a means to achieve specific objectives. These objectives include reducing carbon emissions, fostering economic development in communities, or generating profits for businesses. For instance, in the context of residential solar systems, their adoption is linked to a lower risk of experiencing energy poverty (Hammerle; Burke, 2022). Moreover, PV adoption not only impacts the adopter but the entire society. Despite the energy benefits, several studies have found that incentive policies for solar systems exhibit regressive characteristics, as the distribution of PV adoption tends to skew towards wealthier households (Andor; Frondel; Vance, 2015; Böhringer; Landis; Angel Tovar Reaños, 2017; Cludius et al., 2014; Farrell, 2021; Nelson; Simshauser; Kelley, 2011; Nelson; Simshauser; Nelson, 2012; Strielkowski et al., 2019; Strielkowski; Štreimikienė; Bilan, 2017; Többen, 2017). Consequently, achieving a more equitable distribution in the adoption of PV systems can also help mitigate the cost shift associated with incentive policies.

While numerous studies have addressed inequality in the adoption of rooftop solar systems, a recent systematic review (Konzen; Best; De Castro, 2024) has identified several areas warranting further exploration. These include: (i) a focus on developing countries; (ii) comparisons between countries; and (iii) emphasis on the evolution of PV adoption inequality over time. In this sense, to contribute to this field, we evaluate the inequality and its evolution in the adoption of grid-connected PV systems within two distinct contexts: Australia and Brazil. Australia stands as a leading country in terms of installed PV capacity per capita, boasting a developed economy and a lengthy history of incentive policies for distributed PV. In contrast, Brazil is a developing economy with more recent regulations governing the use of grid-connected PV systems. Nevertheless, the Brazilian PV market has experienced significant growth in recent years, positioning Brazil as a key global player in the PV industry. In 2022, Brazil secured the 4th position in terms of added PV capacity, trailing only China, the USA, and India. Furthermore, both countries exhibit robust growth in the distributed segment, propelling the overall expansion of the solar market (IEA PVPS, 2023). Therefore, our study aims to answer how inequality in the adoption of grid-connected residential photovoltaic (PV) systems has evolved in Australia and Brazil, and how these trends compare between a developed and a developing economy.

Despite the flourishing Brazilian PV market, there is scarce evidence on residential PV adoption inequality in Brazil. According to Konzen et al. (2024), only three peer-reviewed articles have delved into this topic in Brazil (Chueca et al., 2023; Costa; Santos, 2020; De Freitas, 2022). However, these studies faced a limitation in terms of aggregate data. They were conducted at the state, municipal, or census tract level. In this sense, existing literature has demonstrated that studies with aggregated data can yield different results than those at the household level (Best; Chareunsy, 2022). This problem is also known as the ecological fallacy (Robinson, 1950).

In contrast to Brazil, Australia boasts an extensive body of literature on the characteristics of rooftop solar adopters and the inequality in PV adoption. In the early 2010s, Nelson et al. (2011) highlighted a significant concentration of solar systems in high-income households, concluding that incentive policies were regressive in their impact on Australian society. Some studies have reported either no (Lan; Gou; Lu, 2021) or negative (Zhang et al., 2023) relationships between income and rooftop solar adoption. However, these analyses were performed at the postcode level. Utilizing household-level data, a limited number of studies found a positive relationship between rooftop solar uptake and income or wealth (Best; Chareunsy, 2022; Best; Nepal; Saba, 2021; Tidemann et al., 2019). Furthermore, a handful of studies explored the evolution of the role of income in PV adoption (Best, 2022a; Best; Burke; Nishitateno, 2019; Best; Chareunsy; Li, 2021), but over relatively close time periods. The investigation into the change in PV inequality in Australia over a more extended period (2012-2020) is a recent addition to the literature (Best; Chareunsy; Taylor, 2023a, 2023b). In their separate analyses of homeowners and renters, the authors observed persistent inequality for the lowest net-wealth decile homeowners and a widening adoption gap between low and high-wealth renters.

While research on rooftop solar adoption in Australia exists, we contend that there is ample room for new contributions to this field. Firstly, a comparative analysis between two countries is welcomed to contextualize the results (Konzen; Best; De Castro, 2024). By employing similar variables, datasets, and methods, we facilitate the comparison of outcomes across different contexts. Secondly, we delve further into the evolution of PV adoption inequality. In addition to the adoption probability gap in percentage points (Best; Chareunsy; Taylor, 2023a, 2023b), we also use two additional approaches. We scrutinize changes in the distribution of adopters among income quintiles and propose a Solar Gini index to facilitate cross-country comparisons of PV inequality and its evolution over the years. Thirdly, the assessment of inequality in developing countries, particularly using household-level data, remains limited in the existing literature (Konzen; Best; De Castro, 2024). Our study on Brazil aims to address this gap.

Section 2 provides a contextualization of the characteristics of the two countries. It encompasses the evolution of energy policies aimed at promoting the adoption of residential PV. The research methodology is detailed in Section 3, covering the datasets and the three approaches utilized to evaluate the evolution of PV inequality over time. Section 4 presents the main results. The discussion in Section 5 then situates the findings within the existing literature. This discussion highlights implications, strengths, and limitations of our study. The last section concludes with a summary and outlines opportunities for future research.

3.2 Countries profile and policy background

Australia and Brazil share certain similarities, yet they also exhibit significant differences. Both countries possess expansive territories, rich biodiversity, high levels of solar irradiation, and economies significantly reliant on the export of primary commodities (Australian Government, 2022a; MDIC, 2023; Secretariat of the Convention on Biological Diversity, 2001; World Bank, 2020, 2023). Nonetheless, notable disparities exist, primarily in terms of socioeconomic indicators. As illustrated in Table 6, Australia’s Gross national income (GNI) per capita is over seven times greater than Brazil's. Furthermore, Brazil experiences greater income inequality, as indicated by its higher Gini index.

In the context of the energy sector, Table 6 reveals a significantly higher contribution of renewable energy sources to electricity production in Brazil compared to Australia. This discrepancy is primarily attributed to the substantial presence of hydroelectric power within the Brazilian energy mix. However, when excluding hydroelectricity, both nations exhibit a comparable share of renewables in their energy generation. Despite this similarity, each country has pursued a slightly divergent trajectory in introducing new technologies into their energy mix over the past two decades. Australia has predominantly focused on the development of wind and photovoltaic technologies, especially small-scale photovoltaic power plants. In contrast, Brazil has actively promoted the adoption of wind and biomass technologies, with a notable surge in the solar energy sector in recent years (Australian Government, 2022b; EPE, 2023a).

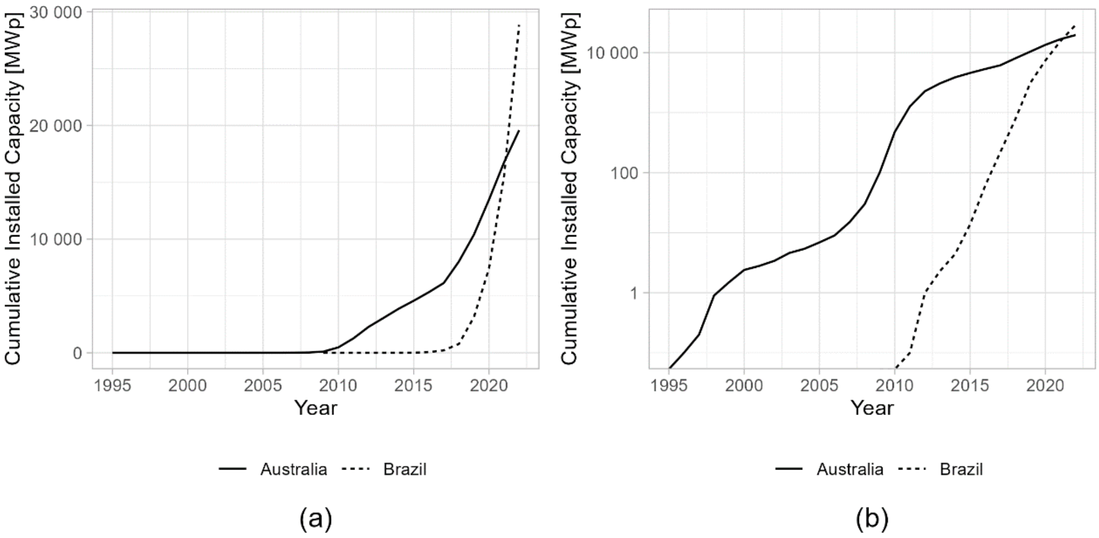
Table 6 – An overview of economic and energy statistics of Australia and Brazil

Item	Australia	Brazil	Year	Unit
Area	7,741,220	8,515,770	2018	km²
Population	26.0	215.3	2022	Millions
Dwelling stock	10.9	90.7	2022	Millions
Gross national income (GNI) per capita	60,710	8,440	2022	USD per capita
Central bank interest rate	4.35	11.75	2023	%
Gini index	34.3%	52.9%	2018	%
CO2 emissions per capita	14.8	1.9	2020	metric tons per capita
Electricity production	265.6	656.1	2021	TWh
Electricity production per capita	10,221.9	3,047.2	2021	kWh/year per capita
Renewable electricity production	26.7%	77.4%	2021	% of total
Renewable electricity production without hydroelectricity	20.9%	22.1%	2021	% of total
Electrification (access to electricity)	100.0%	99.5%	2021	% of population
Average global horizontal irradiation (GHI)	5.76	5.39	2020	kWh/m²/day
Proportion of dwellings with photovoltaic energy	27.8%	1.8%	2022	% of total dwellings

Source: Developed by the authors based on data from different sources (ABS, 2022; ANEEL, 2023; APVI, 2023; Australian Government, 2022b; EPE, 2023a; IBGE, *[S.d.]*; Trading Economics, 2024; World Bank, 2020, 2023).

As shown in Figure 4, Australia initiated the deployment of decentralized photovoltaic (PV) systems connected to the grid considerably earlier than Brazil. In chart (b), a logarithmic scale was employed on the y-axis to underscore the initial phase of the diffusion process. When Brazil established regulations permitting the connection of distributed generators to the grid in 2012, Australia had already an installed capacity exceeding 2 GW.

Figure 4 - Grid-connected decentralized PV installed capacity comparison. Chart (b) uses a logarithmic scale in y axis.



Source: Own elaboration based on ANEEL and APVI data (ANEEL, 2023; APVI, 2021, 2023)

In recent years, Brazil has witnessed a remarkable expansion of its decentralized solar market, surpassing Australia in terms of overall installed capacity. However, it is essential to take into account the following points: (i) Figure 4 encompasses decentralized PV systems across all sectors, not limited to residential installations; (ii) The average decentralized PV system size in Brazil is four times larger than in Australia, with an average of 22.1 kWp/system compared to 5.8 kWp/system (ANEEL, 2023; APVI, 2023). This disparity may be attributed to size limits imposed by the primary incentive mechanisms in both countries: 3 MW in Brazil and 100 kW in Australia (Australian Government, 2023a; BRASIL, 2022); (iii) Brazil has nearly nine times more households than Australia. Therefore, when focusing solely on the residential sector, Brazil still lags behind, as demonstrated in Table 6, with a considerably lower percentage of households equipped with PV systems.

In the forthcoming sections, we will elucidate the main incentive policies for grid-connected residential photovoltaic systems implemented in both countries. This narrative review was conducted primarily through the exploration of documents and websites belonging to governmental bodies, energy agencies, and relevant associations. The primary aim of this analysis is to examine and outline the primary policies driving the adoption of rooftop solar in both countries, rather than evaluating their economic efficiency or passing judgment on their effectiveness.

3.2.1 Australia

Australia’s electricity market is primarily segmented into three regions: the National Electricity Market (NEM), the Wholesale Electricity Market (WEM), and the Northern Territory Electricity Market (NTEM). The NEM interconnects the six eastern and southern states and territories, accounting for approximately 80% of the nation's total electricity consumption (Australian Government, *[S.d.]*). Across most regions of the country, these markets operate within a competitive framework, featuring distinct entities for electricity generation, transmission, distribution, and retail services. However, it is noteworthy that in many areas of the country, the same company assumes the roles of both generator and retailer, commonly referred to as 'gentailers'. Despite the segregation of activities, all associated costs are ultimately passed on to customers by the retailer (APVI, 2023), through a tariff structure encompassing both fixed charges ($/day) and variable charges ($/kWh) (Australian Government, *[S.d.]*).

Time-of-use tariffs (ToU) are accessible in many regions of the country, yet their adoption remains limited. According to a study conducted by the Australian Competition and Consumer Commission (ACCC, 2022), which focused on customers in Victoria (VIC), New South Wales (NSW), South Australia (SA), and southeast Queensland, approximately one-quarter of residential customers have smart meters. However, among this group, only 23% of households have opted for ToU tariffs.

In the financial year 2000-2001, Australia's electricity generation was primarily reliant on fossil fuels (mainly coal), with renewables contributing just 8% (Australian Government, 2022b). However, starting from the late 20th century, Australia made numerous commitments to promote renewable energy generation and reduce greenhouse gas emissions, particularly through initiatives such as the Renewable Energy Target (IEA, 2023). Consequently, by 2020-2021, renewables accounted for 27% of the overall generation mix. As detailed in the subsequent sections, numerous incentives were directed towards the decentralized photovoltaic (PV) sector, including capital subsidies and feed-in tariffs. Consequently, small-scale PV systems now account for one-quarter of the country's renewable energy generation (Australian Government, 2022b).

3.2.1.1 Capital subsidies

In the year 2000, the Australian Government introduced the Photovoltaic Rebate Program (PVRP) with the aim of providing financial incentives to support homeowners and owners of community-use buildings in their investment in PV systems. Despite these efforts, the program experienced a period of low and stable application numbers for several years. However, in 2007, following the election of a new government, the program underwent a rebranding and was renamed the Solar Homes and Communities Program (SHCP). Additionally, the rebate rate was doubled, increasing from \$4.00/W to \$8.00/W, with a maximum rebate cap of \$8,000 for the initial kilowatt (IEA, 2009). This subsidy had the potential to cover up to 80% of the upfront capital costs. The significant increase in the rebate rate led to an overwhelming surge in program applications within a short period, ultimately necessitating the government to suspend the program in June 2009 due to oversubscription (The Australia Institute, 2010). It is worth noting that to be eligible for the SHCP, households were required to have an annual income of less than \$100,000 (IEA, 2009).

It is noteworthy to highlight that Australia has had the Renewable Energy Target (RET) in place since 2001, with the primary objective of promoting the adoption of renewable energy by establishing tradable certificates. However, as of 2009, its impact on the small-scale segment remained relatively modest. As described by the Australian Government(2023c), “through the scheme, large renewable power stations and the owners of small-scale systems are eligible to create certificates for every megawatt hour of power they generate—creating the 'supply' side of the certificate market. Wholesale purchasers of electricity, mainly electricity retailers, buy these certificates to meet their renewable energy obligations—forming the 'demand' side of the certificate market. Wholesale purchasers of electricity then surrender these certificates to the Clean Energy Regulator in percentages set by regulation each year.”. Given this framework, the costs associated with the RET are incorporated into electricity tariffs, except for specific categories of industrial electricity consumers (APVI, 2021).

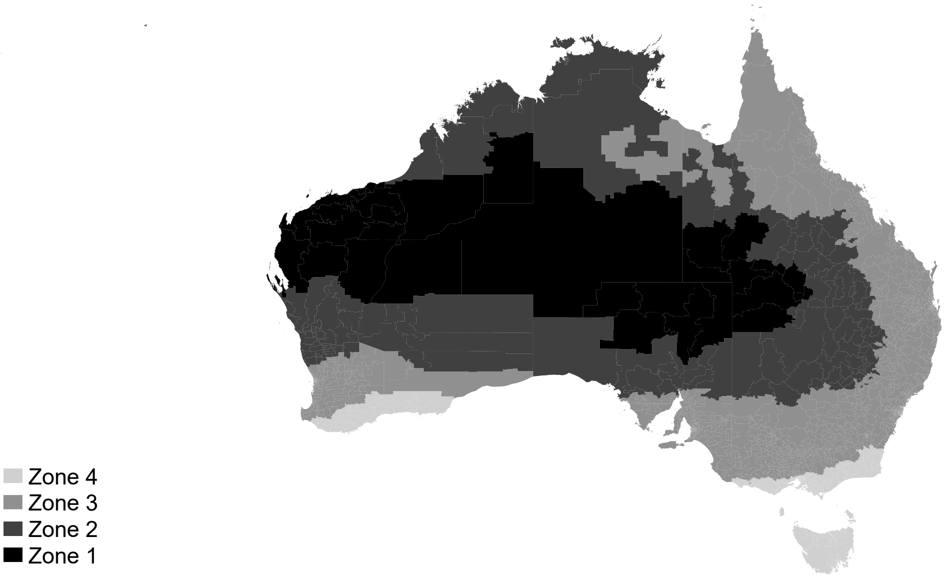
The Renewable Energy Target (RET) gained prominence in the small-scale market when the Commonwealth Government introduced the Solar Credits mechanism in 2009, as an immediate replacement for the SHCP program. Solar Credits introduced a multiplier, initially set at five, for certificates generated by small-scale generators. Under this mechanism, in conjunction with the Renewable Energy Act, homeowners became eligible to receive upfront certificates equivalent to 15 years' worth of certificates. This effectively acted as a rebate mechanism, alleviating the initial investment costs, akin to previous programs such as SHCP and PVRP.

According to the Australian Government (2012), the multiplier was established to provide an upfront capital cost subsidy of approximately \$7,500 for each system. However, as the number of installations surged, the issuance of credits also escalated rapidly, leading to a decline in their market price. This diminishing credit price began to deter investments, particularly in large-scale projects. Consequently, in response to these outcomes, the government opted to reduce the credit multiplier in 2011 and eventually terminated the multiplier mechanism starting from 2013. Additionally, in 2011, the RET was split into two distinct schemes: the Small-scale Renewable Energy Scheme (SRES) and the Large-Scale Renewable Energy Target (LRET). This measure delineated the two schemes, enabling them to operate independently, without competition between the two categories of generators (Australian Government, 2012).

Despite the conclusion of the Solar Credits mechanism in 2013, the Renewable Energy Target (RET) has persisted and continues to serve as the primary form of capital subsidy for small-scale photovoltaic (PV) systems to this day. It is important to note that the RET has a predetermined completion date of 2030, which means that new PV system adopters will receive progressively fewer certificates as we approach this end date. For instance, a new system installed at the beginning of 2023 would be eligible for certificates for a duration of eight years (Australian Government, 2023b). To provide some context, since its inception in 2011, the small-scale technology certificate (STC) has typically maintained a price close to the cap of $40, as set by the Clean Energy Regulator. However, during certain months in 2011 and 2012, due to an oversupply of certificates, the price temporarily dipped below $30 (Australian Government, 2017; Demand Manager, 2023).

It is crucial to emphasize that the certificates are allocated upfront based on the expected generation rather than the actual generation of the photovoltaic (PV) system. To account for varying irradiation levels across the country, Australia has been divided into four zones, with a specific generation factor assigned to each zone (see Figure 5). For instance, consider a 6.6 kWp PV system located in Sydney (zone 3). This system is expected to generate approximately 9.1 megawatt-hours (MWh) per year, which is calculated as the product of 6.6 kWp and the factor 1.382. For a system installed in 2021, it would be eligible to receive certificates for a duration of 10 years, spanning from 2021 to 2030. This would result in the issuance of 91 certificates. At a value of $35 per certificate, this household would have received a subsidy amounting to $3,185 (Solar Choice, 2020).

Figure 5 - SRES zones operating since January 1, 2020



Note: The SRES factors are 1.185, 1.382, 1.536, and 1.622 for zone 4, 3, 2, and 1 respectively.
Source: Best and Burke (2023)

In addition to the federal capital subsidy scheme (SRES), numerous cities, states, and territories in Australia have implemented various rebate programs for solar installations in recent years. Here are some examples:

a) New South Wales (NSW): The state of New South Wales offers the "Rebate Swap for Solar" program, which provides a free 3 kW solar system to pensioners in exchange for their current low-income bill rebate (NSW Government, 2023).

b) Victoria: In Victoria, the government offers a rebate of up to $1,400 and the option of an interest-free loan to eligible households and rental property owners for installing solar panels. The eligibility criteria are relatively broad, allowing homeowners with an annual income of up to $210,000 and properties valued up to $3 million to participate (Solar Victoria, 2023).

c) Australian Capital Territory (ACT): The ACT provides a rebate of 50% of the total installation cost, up to $2,500, for rooftop solar installations, along with a zero-interest loan. However, to be eligible, the resident must be a pensioner, veteran, or hold an Australian Government Health Care Card (ACT Government, *[S.d.]*).

d) Adelaide: The city of Adelaide has introduced a 20% rebate program for solar installations, offering rebates of up to $5,000 (varies based on the system size). This rebate is also applicable to shared solar projects (APVI, 2023).

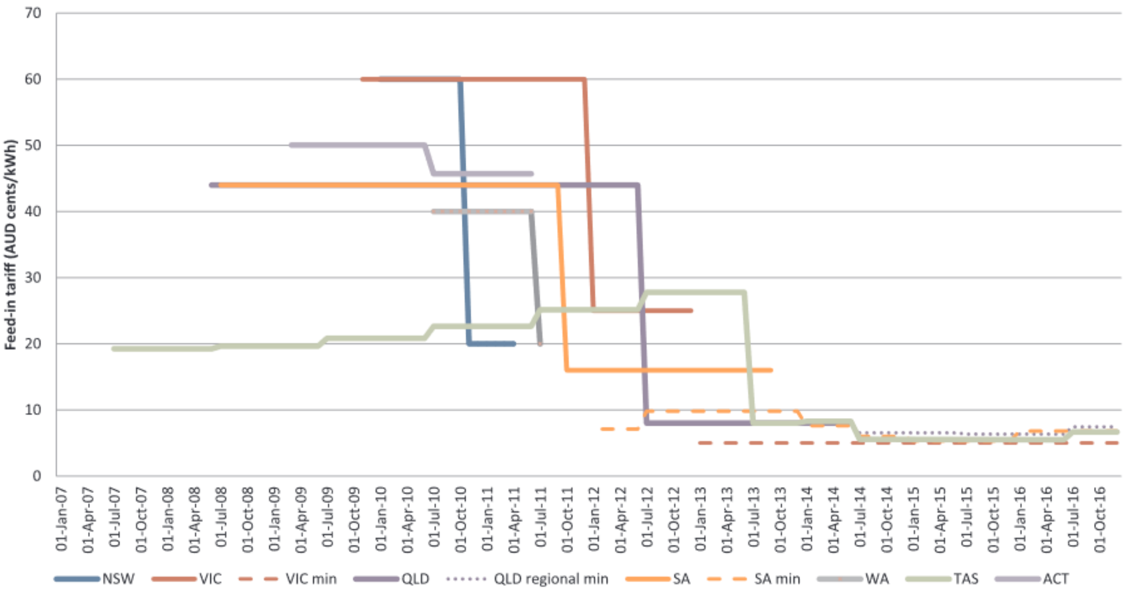
It's noteworthy that there is a growing trend in recent years to target vulnerable populations with these solar rebate policies, aiming to make renewable energy more accessible and affordable to a wider range of residents (APVI, 2023). According to APVI (2019, 2020), the first measures for solar for low-income households were introduced by state governments in 2019 in Australia.

3.2.1.2 Feed-in Tariffs

In addition to the capital subsidies that have been in place for over two decades, another mechanism that has had a notable impact on the uptake of rooftop solar installations in Australia is the feed-in tariff. Commencing in 2008, this mechanism allowed electricity generators to inject surplus electricity into the grid and receive compensation for it. However, unlike effective capital subsidies, which have continued to include the nationally regulated SRES, feed-in tariffs are determined independently by each state or territory. Due to this decentralization, the values and metering methods associated with feed-in tariffs have exhibited significant variations over time across different regions. In certain areas, a gross metering approach was employed, where the entire electricity generation from the solar system was compensated at the feed-in tariff rate. Conversely, in other regions, only the surplus electricity generated after meeting household consumption needs was metered and eligible for feed-in tariff compensation (IEA, 2009; Poruschi; Ambrey; Smart, 2018).

When feed-in tariffs were initially introduced, their values were set above the retail electricity tariffs, which provided a substantial incentive for solar adoption but also raised concerns about the program's cost. As depicted in Figure 6, governments subsequently initiated abrupt reductions in feed-in tariffs. Consequently, the so-called premium tariffs, which were set above retail tariffs, ceased to be available by 2014 (Poruschi; Ambrey; Smart, 2018). Following the discontinuation of premium tariffs, the majority of solar systems began receiving feed-in tariffs based on the wholesale electricity price. Despite this reference price, today, each electricity retailer offers its own feed-in tariff rates to customers, which generally exceed the wholesale price due to customer acquisition and retention strategies (APVI, 2021). To illustrate this, a quick search in September 2023 for postcode 2113 in New South Wales (NSW) yielded a range of offers for exported electricity, from $0.01/kWh to $0.12/kWh. Furthermore, it's worth noting that these offers can go as high as $0.30/kWh for customers who have a battery system (Solarquotes, 2023). By way of comparison, the average wholesale electricity price in NSW for September 2023 was approximately $0.08/kW (AEMO, *[S.d.]*).

Figure 6 - Evolution of regulated feed-in tariffs in Australian states.



Source: Poruschi, Ambrey and Smart (2018)

As feed-in tariffs declined to levels below retail electricity rates, consumers were incentivized to maximize self-consumption of the electricity generated by their solar systems, using the energy directly within their households. This practice has been permitted in all Australian jurisdictions for over a decade (APVI, 2014, 2023). To further enhance the level of self-consumption, PV system owners have been investing in energy storage solutions such as batteries to store excess electricity generated during the day for later use. Notably, some states have introduced subsidies for residential battery installations in recent years to encourage the adoption of this technology (APVI, 2023).

3.2.2 Brazil

Brazil is predominantly connected to the National Interconnected System (SIN), with only 0.6% of the national electricity consumption originating from isolated systems, primarily concentrated in the northern region of the country (EPE, 2023b). In Brazil, customers supplied at low voltage, which mostly includes residential, commercial, and rural customers, do not have the option to select their electricity retailer. These customers, often referred to as captive consumers, are served by the distribution companies responsible for procuring electricity from generators and passing on the associated costs to their customers (Brasil, 1995; MME, 2022a). The captive market in Brazil accounts for 60% of the total electricity consumption, while the remaining 40% is attributed to customers served at high voltage who have the freedom to choose their electricity retailer (Brasil, 1995; EPE, 2023b; MME, 2022a).

Residential electricity tariffs in Brazil are entirely volumetric, denominated in ($/kWh). However, a minimal usage requirement is imposed, ranging from 30 kWh/month to 100 kWh/month, according to the consumer's electrical connection type (ANEEL, 2021). Time-of-use tariffs became optional for all low voltage customers in Brazil starting in 2020. Nevertheless, as of July 2023, only 0.1% of customers have opted for this tariff structure (ANEEL, *[S.d.]*, *[S.d.]*).

The electricity sector in Brazil has had a strong reliance on renewable energy sources since the early 20th century, primarily driven by the use of hydroelectric power plants (Centro da Memória da Eletricidade no Brasil, 2000). In 2022, renewable sources accounted for 88% of total electricity generation, a percentage similar to that in 2000. However, it's important to note that the share of hydroelectric power has been gradually decreasing over the years, declining from 87% to 63% over the same period. Conversely, wind and solar energy have seen substantial growth, going from virtually zero in 2000 to a 17% share of total electricity generation in Brazil in 2022, primarily from large-scale projects. Despite the significant progress illustrated in Figure 4, decentralized photovoltaic (PV) solar still constitutes only 3% of the total electricity generation (EPE, 2023a). It's worth highlighting that due to Brazil's historically high reliance on renewables, one of the main motivations for diversifying the electricity mix was to reduce vulnerability to hydrological cycles, especially after the energy supply crisis in 2001 (Poque González; Viglio; Da Costa Ferreira, 2021). However, the PROINFA program, a significant initiative launched in the early 21st century to boost investments in new energy technologies, initially excluded solar due to its high cost at that time (ABINEE, 2012). Consequently, as illustrated in the subsequent sections, the primary incentive mechanism for decentralized solar energy was introduced later, in 2012.

3.2.2.1 From net-metering to net-billing

While Australia primarily utilizes the feed-in mechanism as the main method to compensate for electricity injected into the grid, Brazil has chosen to implement the net-metering scheme. According to IEA PVPS (2016), net-metering is an incentive scheme that allows for the compensation of energy production and consumption over an extended timeframe, often up to one year or more. Consequently, customers under net-metering arrangements do not receive an explicit tariff in monetary terms ($/kWh) for the electricity they export; instead, they receive a credit in energy units (kWh) to offset their subsequent consumption. However, in financial terms, it is as if the exported energy were sold at the retail electricity price.

In 2012, the Brazilian Electricity Regulatory Agency (ANEEL) introduced Normative Resolution n° 482/2012 (REN 482), which regulated the connection of decentralized power plants to the distribution grid and established the net-metering scheme. Notably, during that period, ANEEL did not consider the net-metering scheme as a subsidy, and REN 482 had a neutral approach, focusing solely on permitting the connection of small-scale generators to the distribution grid (ANEEL, 2011).

In the beginning, the REN 482 was applicable to renewable energy sources and cogeneration plants with a capacity of up to 1 MW. During that period, customers were granted up to three years to utilize their energy credits. Additionally, a distinctive feature of the Brazilian net-metering system was the option to employ these credits either on-site or in a different building of the same owner, as long as it was located within the service area of the same distribution company (ANEEL, 2012). Subsequently, in 2015, this scheme was reviewed. The power limit was increased to 5 MW, and the compensation timeframe was extended to five years. Another significant change introduced in 2015 was the introduction of the virtual net-metering mechanism, allowing for the sharing of credits among members of a shared power plant (ANEEL, 2015).

As seen in Figure 4, decentralized photovoltaic (PV) capacity in Brazil started to experience significant growth after 2017. Due to the potential impacts of this subsidy mechanism, ANEEL initiated discussions regarding a new revision of the net-metering scheme in 2019 (ANEEL, 2019b). However, owing to the magnitude of the debate, the Brazilian Congress intervened and addressed the matter through the enactment of a new law. Law n° 14,300/2022 (BRASIL, 2022) maintained the primary characteristics and procedures of the existing model but introduced a progressive charge for new installations to cover distribution costs from 2023 to 2028. An exception applies to systems exceeding 500 kW for remote compensation, for which charges are more substantial and immediate. Subsequently, after 2028, the compensation for all systems installed from 2023 onward will be determined based on a cost-benefit analysis. This assessment will encompass the effects of decentralized power plants on the generation, transmission, distribution, and power losses costs of the Brazilian power system. Hence, following the definition provided by Zinaman et al. (2017), this compensation framework, in which the net exported electricity is generally valued lower than the retail rate, can be classified as a net-billing scheme.

An important aspect to highlight is that Law No. 14,300/2022 (BRASIL, 2022) has also implemented a program aimed at installing distributed generation systems to benefit low-income households. As per the law, distribution companies are mandated to organize auctions to engage companies in installing and operating small-scale generators. The generated power will be directed to low-income households under the net-billing scheme, and any excess electricity may eventually be sold back to the distributors. The program's costs will primarily be covered by an existing energy efficiency fund. However, the program is not yet operational, awaiting further regulatory rulings.

3.2.2.2 Tax incentives

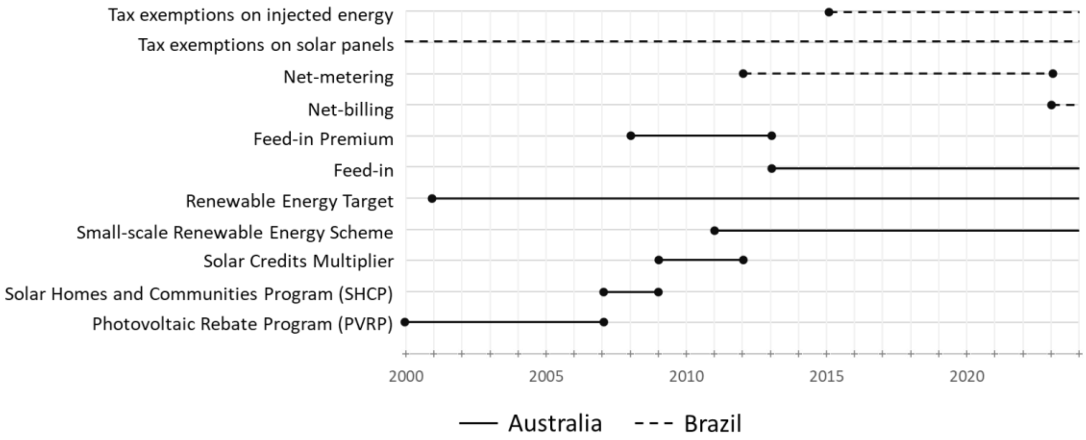
Since 1997, Brazil has implemented an exemption from ICMS (a state tax on the circulation of goods and services) on operations involving solar panels, solar water heaters, and wind generators (CONFAZ, 1997). This measure has led to a reduction in the initial capital costs associated with these technologies. However, prior to the establishment of the net-metering scheme for grid-connected distributed generation, this incentive primarily benefited off-grid applications.

Another set of tax incentives is directed at electricity exported to the grid from decentralized PV systems. At the inception of the net-metering scheme in Brazil in 2012, states were calculating ICMS based on the gross consumption of electricity. In other words, the excess electricity generation injected into the grid, when compensated, was subject to taxation. Nevertheless, starting in 2015, some states began exempting this portion of the generation from ICMS, levying tax only on the net consumption. By 2018, all states had adopted this approach, which remains in effect today (CONFAZ, 2015). The federal government took a similar step by exempting federal taxes (PIS/COFINS) on the injected generation in 2015 (Brasil, 2015). For context, taxes (ICMS and PIS/COFINS) accounted for an average of 23% of residential electricity bills in 2022 (ANEEL, *[S.d.]*).

3.2.3 Summary and discussion

As demonstrated in the preceding sections, both countries have embraced distinct policies to encourage the adoption of rooftop solar energy. Australia placed particular emphasis on direct subsidies and feed-in tariffs, whereas Brazil has pursued an approach centered around net-metering and tax exemptions. Figure 7 provides a summary of the primary countrywide incentive policies for grid-connected residential PV systems in both countries spanning the period from 2000 to 2024.

Figure 7 - Time frame of the main incentive policies to residential PV in Australia and Brazil from 2000 to 2024



Source: Own elaboration.

It is worth noting that, according to the IEA (2009), before the introduction of feed-in tariffs, most electricity retailers in Australia provided net-metering arrangements for small renewable energy generators connected to the electricity distribution grid. However, this scheme didn't offer significant incentives to investors and quickly became overshadowed by the more attractive premium feed-in tariffs. Then, after the reduction in feed-in tariffs in 2014, net-metering remained as an option in Australia until 2020 (APVI, 2021, 2022), but with a mere 30-minute compensation timeframe for energy flows (APVI, 2017). This limited timeframe makes it challenging to fully utilize excess daytime generation to offset nighttime electricity consumption effectively. In fact, some definitions of net-metering, such as in Zinaman et al. (2017), require a netting frequency of at least the billing cycle. Therefore, given the controversy regarding the definition of net-metering and the low popularity of this scheme in Australia, it was not considered a significant incentive policy in this study.

Despite the distinct characteristics of the incentives offered in each country, it is crucial to consider the extended deployment timeframe as a key factor explaining why Australia currently holds the global leadership position in terms of photovoltaic (PV) capacity per capita, with 1.18 kW installed per capita (APVI, 2021). Drawing upon the Diffusion of Innovations theory (Rogers, 2003), it becomes evident that the initial stages of the diffusion process progress gradually, primarily driven by innovators. These early phases play a pivotal role in introducing the new technology to society, subsequently attracting imitators to enter the market.

Consequently, Australia's early entry into the solar market conferred upon it a substantial advantage relative to Brazil.

As the deployment of incentive policies proved successful, Australia began to phase out its subsidies starting in 2014. It transitioned to offering feed-in tariffs that closely mirror wholesale electricity prices and reducing renewable energy certificates annually. In contrast, Brazil maintained its compensation mechanism at the full retail rate until 2022, initiating a gradual reduction in compensation values for new adopters in 2023. Brazil is set to implement a compensation system based on the actual value of distributed generation for the system only after 2028. Consequently, the shift to a market-based compensation approach will occur in Brazil considerably later than in Australia.

It is noteworthy that Australia formulated its incentive policies with the primary objective of bolstering the participation of renewable energy and reducing greenhouse gas emissions from its coal-based energy mix. In contrast, Brazil already possessed a predominantly renewable generation mix. As a result, Brazil introduced its net metering scheme in 2012, taking a neutral approach by allowing the connection of small-scale generators to the distribution grid. At that time, the net metering scheme was not regarded as a subsidy by the regulator, and society held the perception that this scheme was insufficient to stimulate the adoption of distributed generation (ANEEL, 2011). However, over time, it became evident that full retail tariff compensation served as a substantial incentive for decentralized PV adoption in Brazil.

3.3 Methodology

To enhance the rigor of our analysis, we have employed a multiple methods approach, which is considered a good practice in the field of energy social sciences (Sovacool; Axsen; Sorrell, 2018). First, we utilize descriptive statistics, a common tool in social sciences, to provide an initial understanding of the data (Agresti, 2017). Second, to facilitate the evaluation and comparison of PV adoption inequality across different contexts, we introduce a Solar Gini index. This index is based on the traditional Gini index used to measure economic inequality and is inspired by similar studies conducted by Chueca et al. (2023) and Grover and Daniels (2017). Finally, we apply a series of regression models to obtain more detailed insights. Through these models, we can, for instance, analyze PV inequality across income quantiles while controlling for other variables, such as education, housing type, and homeownership. The integration of these three methods, combined with the use of household-level data, represents a novel approach in the PV inequality literature, lending robustness to our conclusions and offering a model for future research. More details on these three methods are provided in section 3.2.

3.3.1 Data

For Brazil, we utilized the microdata from the Continuous National Household Sample Survey (PNAD-C) provided by IBGE (IBGE, *[S.d.]*). Since 2016, this survey includes a question about whether the household has its own source of electricity generation. To align with the research focus on grid-connected systems, households without access to electricity or not connected to the grid, constituting 1.0% of the sample, were excluded from the database. It is essential to note that the survey does not specify the source of generation. However, we confidently associate our results with solar power, given its predominant use, accounting for nearly 100% in the residential sector, among distributed generation capacity installed in Brazil (EPE, 2023c). While PNAD-C is conducted quarterly, essential household characteristics are surveyed only once a year, typically during the first household visit. Hence, for the purposes of this study, we will consider an annual periodicity. In addition to gathering data on distributed generation use, PNAD-C also collects socioeconomic information such as average income, years of schooling, age, ethnicity, dwelling type, and tenure structure. The data covers the period from 2016 to 2022, with the most recently published survey being from 2022. However, due to the Covid-19 pandemic, microdata for 2020 and 2021 are unavailable.

Regarding Australia, the primary database used is the detailed microdata from the Survey of Income and Housing (SIH) provided by the Australian Bureau of Statistics (ABS) (ABS, *[S.d.]*). The first edition of SIH that investigates the adoption of PV systems in households is the 2015-2016 survey. Subsequent editions are published every two years, with the most recent being the 2019-2020 edition. Another ABS survey called Household Energy Consumption (ABS, *[S.d.]*) from 2012 will also be utilized to provide adoption data prior to 2015. Thus, this study covers the period from 2012 to 2020.

While some studies suggest that using household wealth is more appropriate than household income (Best; Burke; Nishitateno, 2019; Best; Chareunsy; Taylor, 2023a, 2023b; Best; Nepal; Saba, 2021), the Brazilian database lacks this variable. Consequently, economic inequality is assessed based on the income variable in both the Brazilian and Australian studies to facilitate comparison between the two countries. Moreover, income is commonly employed by policymakers to ascertain eligibility for subsidy programs and may be more practical to use than wealth in certain contexts.

Descriptive statistics in Appendix C Table 16 affirm the observations made in Section 2, highlighting the higher rate of residential PV adoption and greater household income in Australia compared to Brazil. Income is presented in PPP Dollars/month, converted using the OECD index (OECD, 2024) for each country and survey year. Importantly, the exchange rates employed for income conversion do not impact the subsequent analysis; they are utilized in the appendix tables solely to facilitate the income comparison between the two countries. Another notable distinction is the proportion of respondents with a university education, with an average of 41% in Australia in 2019-20 compared to 15% in Brazil as reported in the last survey (2022). Additionally, Table 16 suggests larger houses in Australia, as indicated by a higher number of bedrooms, potentially facilitating solar panel installations. It is interesting to note that despite having fewer bedrooms, dwellings in Brazil accommodate a higher number of residents, indicating a higher density rate. Other characteristics commonly cited in the literature as determinants for PV adoption, such as home ownership and dwelling type, do not exhibit significant differences between the two countries.

The income distribution in quintiles is presented in Appendix C Table 17 for the most recent survey in each country, utilizing sample weights. It is noteworthy that the lower boundary of the most affluent quintile in Brazil (PPP$ 2,555/month) is close to the upper boundary of the first quintile in Australia (PPP$ 2,363/month). This suggests that households in the fifth quintile in Brazil may encounter financial constraints similar to those faced by households in the first two quintiles in Australia when investing in solar.

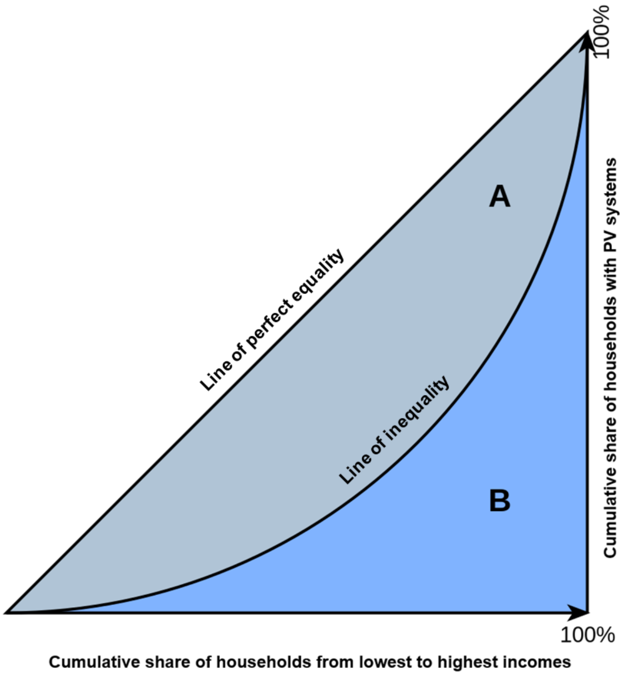
3.3.2 Approaches and principles

We employ three approaches to investigate the inequality in the adoption of residential PV systems in both countries. Each approach is conducted independently for each country.

The first approach involves descriptive statistics, illustrating the residential PV uptake probability by income quintile over the years. Additionally, relative frequency charts depict the distribution of residential rooftop solar systems by income quintile and its evolution. Second, we propose a Solar Gini. This index is rooted in the Lorenz curve (Lorenz, 1905) and Gini index (Gini, 1912), but measures the concentration of residential PV systems across the income distribution. Chueca et al. (2023) introduced a similar index in their work to gauge the concentration of PV project sizes (installed capacity versus the number of PV systems) without considering income. Grover and Daniels (2017) also used Lorenz curves and the Gini index to estimate inequality in PV adoption but at the census level, while our study utilizes household-level data.

To calculate the Solar Gini, we first order the households from the lowest to the highest income for each survey. Subsequently, we compute the (weighted) cumulative household income and the (weighted) cumulative number of solar systems throughout the dataset. These two vectors are then employed to plot the inequality line, as depicted in Figure 8. Finally, Equation 1 outlines how to calculate the Solar Gini index. Similar to the conventional Gini index, a value of 0 signifies perfect equality, while 1 indicates absolute inequality. The inequality curve provides a more detailed illustration of solar adoption across the income distribution, while the Solar Gini serves as a single metric to quantify the concentration level of solar systems among households.

Figure 8 - Example of the Lorenz curve for Solar Gini



Source: Own elaboration.

$$Solar\ Gini = \frac{A}{A+B} = 1 - 2B \qquad (1)$$

The third approach involves a series of regression models. We begin by running regressions for each survey's cross-sectional data to evaluate the probability of solar adoption across quintiles and over time. The preferred model is a Linear Probability Model (LPM), and Probit and Logit models are also employed as robustness checks to account for the dichotomous nature of the dependent variable. However, the results remained similar, so we continue to use the more convenient LPM approach. We chose not to use weights during the main regressions for efficiency reasons (Platt; Harper, 2013). However, weighted regressions were performed for robustness testing and yielded similar results. Equation 2 illustrates the general regression form.

$$S_h = c + \beta Q_h + \gamma \boldsymbol{Z}_h + \varepsilon_h \tag{2}$$

The binary dependent variable, S_h, indicates the presence of a PV system in the household h. The explanatory variable, Q, is a categorical variable representing the income quintile for each household, and $\boldsymbol{Z}$ is a vector of other control variables. The constant term in the regression is denoted as c, and the error term is ε. In terms of control variables, we use the following for both countries: welfare benefit receipt, tenure type, dwelling type, number of bedrooms, number of people, respondent age quintile, and university education of the respondent. In addition to individual controls, we include state and area (living in a capital city or not) control variables to account for regional differences, such as irradiation levels, tariff levels, regional economic development, or state policies. A summary of the variables is presented in Appendix C Table 18.

Next, we combine the four Australian and five Brazilian surveys into two datasets, one for each country, to conduct pooled regressions. To achieve this, we standardized minor differences in variables and definitions across surveys. A categorical variable representing the year of the surveys was added. It is important to note that these datasets do not follow a panel structure since each survey selects different households. Consequently, we are not tracking changes in the same household over time. However, Deaton (2018) suggests that the "time-series of cross-sections" approach can still be valuable for tracking groups over time, such as assessing differences in regions or occupational groups. In our case, we are examining differences across income quintiles. Despite the focus on groups, it's important to highlight that we utilize household-level data, avoiding issues such as the ecological fallacy (Robinson, 1950). The second regression specification is presented in the subsequent section.

$$S_h = c + \beta Q_h + \delta Y_h + \varphi(Q_h \cdot Y_h) + \gamma \boldsymbol{Z}_h + \varepsilon_h \tag{3}$$

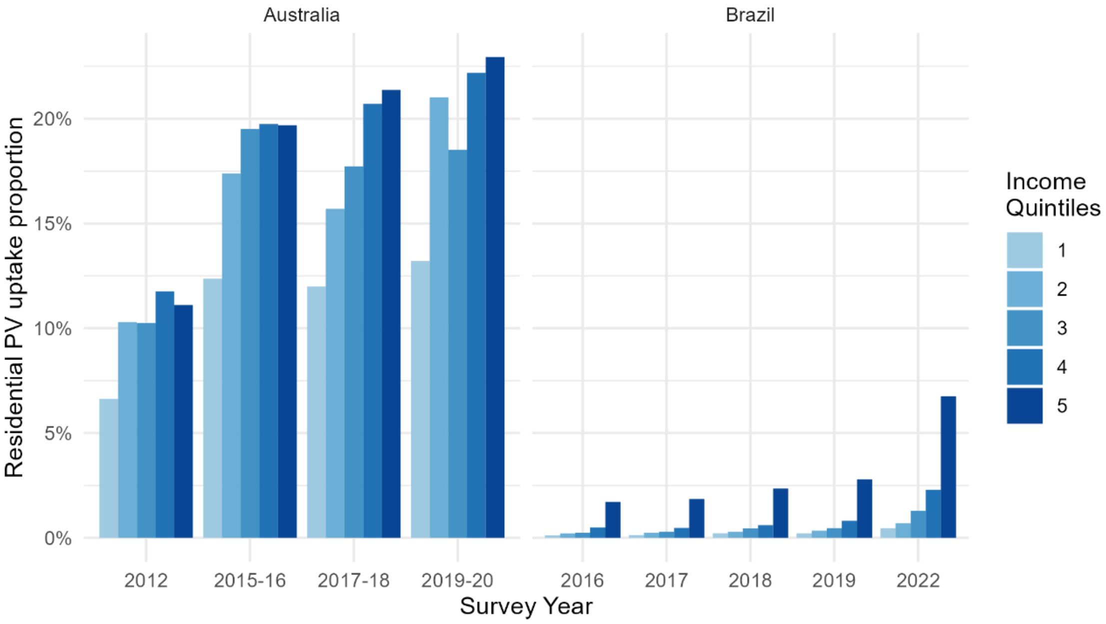
In addition to the variables described in Equation 2, we have introduced the categorical variable Y to represent the survey year. Furthermore, we included an interaction term of Y with a binary variable Q which is positive for households in the fifth income quintile.

3.4 Results

3.4.1 Descriptive statistics

Figure 9 illustrates the adoption of residential PV in Australia and Brazil across income quintiles over time. A noticeable disparity in penetration between the two countries is evident, even within the same quintile groups. Regarding the distribution of the solar systems, in Australia, the uptake appears more evenly distributed across quintiles two to five, with the first quintile displaying lower adoption rates. Conversely, in Brazil, the fifth quintile stands out, exhibiting a significantly higher PV uptake compared to quintiles one to four. Thus, Figure 9 suggests that residential solar adoption is more concentrated in Brazil than in Australia.

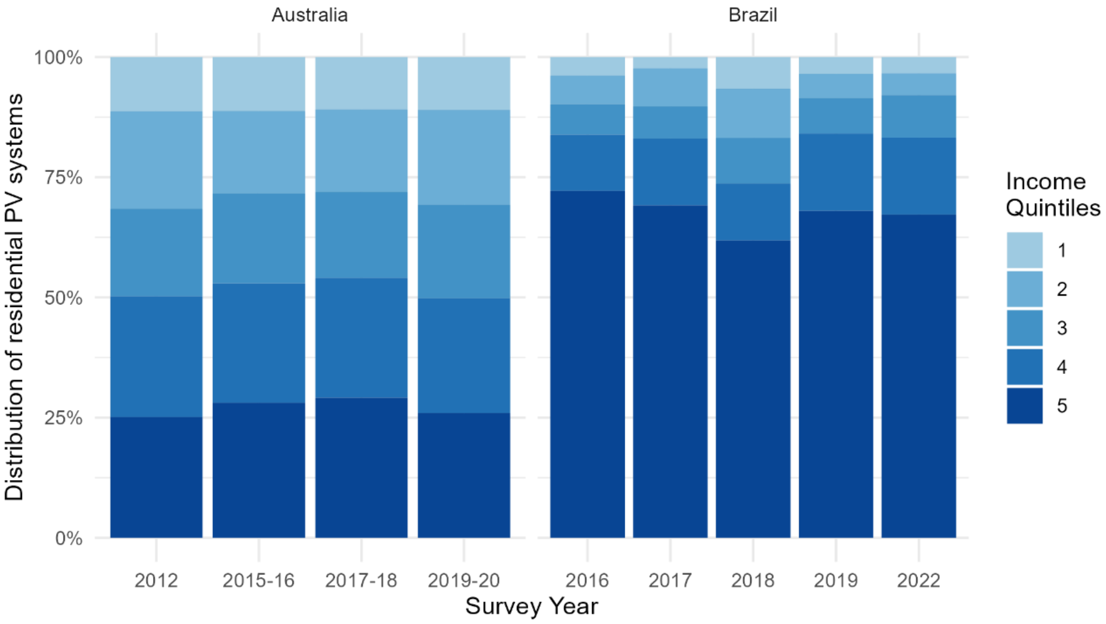
Figure 9 - Residential PV uptake by income quintile in Australia and Brazil



Source: Own elaboration.

Figure 10 reinforces the observation that the distribution of residential solar deployment is more concentrated in Brazil than in Australia. Additionally, it indicates that this distribution has remained relatively stable over time. In Australia, there was a trend of increasing solar share in the fifth quintile from 2012 to 2018; however, in the latest survey (2019-20), the distribution reverted to values similar to 2012. In Brazil, the fifth quintile appears to have lost a small share from 2016 to 2022 to the third and fourth quintiles. Nevertheless, the solar share in the first and second quintiles did not improve. In fact, these disadvantaged groups experienced a slight decline in solar participation over time.

Figure 10 - Distribution of residential PV systems by income quintiles

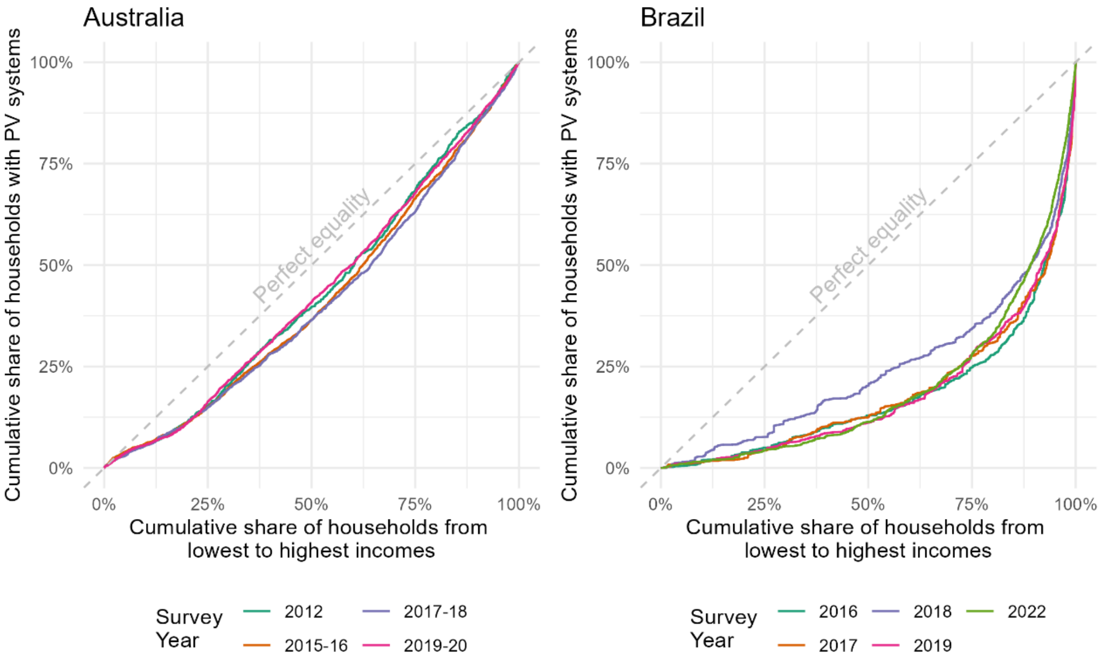


Source: Own elaboration.

3.4.2 Solar Gini index

Figure 11 provides a more detailed perspective on the concentration of PV installations across the income distribution. As suggested earlier, Australia's lines are closer to perfect equality than those of Brazil. For instance, in Brazil, the first 75% of households hold around 25% of the PV systems, whereas in Australia, this proportion is approximately 65%. The chart also reveals minimal changes in the curve pattern over time, particularly in Australia, where the curves for 2012 and 2019-20 are essentially overlapping. In Brazil, the slightly improved equality in 2018 does not seem to persist in subsequent years. This indicates that the result for 2018 might be influenced by survey design and the small percentage of households with solar in Brazil, which amplifies potential sampling variability. Examining the difference between 2016 and 2022 in Brazil, there is a slight reduction in the share of solar in the first 60% of households over the period (green curve below all others). Conversely, above 60%, the green curve surpasses the others, indicating an improved distribution beyond this threshold. Table 7 reinforces these observations, with Solar Gini indexes confirming that Brazil experienced a modest improvement in overall distribution but continues to exhibit significant inequality in solar adoption among households. In contrast, Australia maintains a low Solar Gini, and despite an increasing trend from 2015 to 2018, the index returned to 2012 levels in 2019-20, suggesting a stable distribution over time.

Figure 11 - Cumulative share of households with PV according to income



Source: Own elaboration.

Table 7 - Solar Gini Evolution

Country	Survey Year	Solar Gini
Australia	2012	0.14
Australia	2015-16	0.17
Australia	2017-18	0.19
Australia	2019-20	0.14
Brazil	2016	0.64
Brazil	2017	0.63
Brazil	2018	0.51
Brazil	2019	0.63
Brazil	2022	0.61

3.4.3 Regression analysis

Table 8 and Table 9 present the PV uptake probability by quantile in comparison to the fifth quintile in Australia and Brazil, respectively. In Australia, there is generally no statistically significant difference between quintiles two, three, and four to five. However, the negative result for the first quintile suggests that this group has lower adoption than the fifth quintile, even after controlling for other variables. In Brazil, the significant and negative coefficients for all quintiles indicate a more pronounced inequality in the adoption of residential PV. For 2022, the probability of adoption in Q1 is lower by 4.7 percentage points than Q5.

While this percentage might seem small, it is crucial to note that the overall adoption rate in Brazil is low, even in the fifth quintile (around 6%). Therefore, the shortfall of 4.7 percentage points represents a substantial disadvantage for the lower-income group.

Table 8 - Separate linear probability models explaining residential PV uptake in Australia

	2012	2015-16	2017-18	2019-20
Reference = Q5				
Q1	-0.027*	-0.035**	-0.055***	-0.046***
	(0.012)	(0.012)	(0.013)	(0.013)
Q2	0.011	0.009	-0.008	0.005
	(0.010)	(0.011)	(0.012)	(0.011)
Q3	0.002	0.011	-0.002	0.002
	(0.009)	(0.010)	(0.010)	(0.010)
Q4	0.017*	0.019*	0.012	0.013
	(0.009)	(0.009)	(0.010)	(0.010)
Welfare	-0.001	0.016*	-0.010	-0.001
	(0.007)	(0.007)	(0.008)	(0.008)
Rented	-0.111***	-0.162***	-0.158***	-0.165***
	(0.008)	(0.009)	(0.010)	(0.010)
University	0.026***	0.028***	0.018**	0.014*
	(0.006)	(0.006)	(0.007)	(0.007)
Controls	Yes	Yes	Yes	Yes
Num. Obs.	11978	17768	14060	15011
R^2 Adj.	0.072	0.111	0.111	0.124

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Coefficients for “Rented” are in comparison to outright homeowners. Other tenure types are omitted to save space. Controls include dwelling type, number of bedrooms, number of people, respondent age quintiles, state of residence, and a binary variable for living in a capital city or not.

Table 9 - Separate linear probability models explaining residential PV uptake in Brazil

	2016	2017	2018	2019	2022
Reference = Q5					
Q1	-0.009***	-0.010***	-0.011***	-0.015***	-0.047***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q2	-0.009***	-0.009***	-0.012***	-0.015***	-0.048***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q3	-0.009***	-0.010***	-0.011***	-0.015***	-0.044***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q4	-0.009***	-0.009***	-0.012***	-0.014***	-0.039***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Welfare	0.000	-0.001	0.000	-0.001	-0.005***

	2016	2017	2018	2019	2022
	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)
Rented	-0.002***	-0.004***	-0.005***	-0.006***	-0.014***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
University	0.009***	0.009***	0.012***	0.011***	0.016***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Controls	Yes	Yes	Yes	Yes	Yes
Num. Obs.	149700	150047	150472	149196	131353
R^2 Adj.	0.012	0.013	0.015	0.017	0.034

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Coefficients for “Rented” are in comparison to outright homeowners. Other tenure types are omitted to save space. Controls include dwelling type, number of bedrooms, number of people, respondent age quintiles, state of residence, and a binary variable for living in a capital city or not.

The results in Table 8 and Table 9 reveal differences between the two countries in terms of the influence of a university degree on PV adoption probability. In Australia, the magnitude of the coefficients over time is decreasing and becoming less statistically significant, while in Brazil, the coefficients are significant and increasing in magnitude. One possible explanation for these results is the disparity in the overall PV diffusion rate in each country. Brazil is still in the early stages of the PV diffusion process, and, as per Rogers (2003), early adopters tend to be more educated than late adopters. In Australia, where PV is a mature technology, the influence of education is less relevant. The impact of housing tenure is also evident in the analysis. In both countries, renters have a lower probability of PV adoption compared to outright homeowners. Homeownership is a well-known characteristic with a positive influence on solar adoption (Alipour et al., 2020). Interestingly, receiving a welfare payment has little to no influence on adoption in both countries, when controlling for other variables like income. These findings can be crucial for shaping policies aimed at reducing PV adoption inequality. Specifically, our findings suggest that income should be prioritized as an eligibility criterion before welfare beneficiary status in such policies.

Table 10 presents the results of the pooled regression for the Australian case. In the first column, it is observed that the PV uptake probability increased by 11.8 percentage points from 2012 to 2019-20 for the fifth quintile group (see the Q5&2012 coefficient). Moving to the second column, it is evident that during the same period, the probability increased by 8.7 percentage points for those not in Q5 (see the 2019-20 coefficient). The difference of 3.1 percentage points between the two groups is confirmed in column (2). After adding controls, the difference between the two groups loses significance and magnitude, but it is still 2.5 percentage points and significant at the 0.05 level in column (5). However, after 2012, the difference in the uptake PV probability between Q5 and other quintiles seems to stop increasing, given the insignificant coefficients. This does not imply a reduction in inequality but suggests that between 2015 to 2020, the gap between Q5 and not Q5 remained stable.

Table 10 - Pooled regression coefficients from linear probability models explaining solar panel uptake in Australia; explanatory variables added progressively in each regression

	(1)	(2)	(3)	(4)	(5)
Reference = Q5&2019-20					
Not Q5	-0.074***	-0.046***	-0.033***	0.014+	0.004
	(0.007)	(0.007)	(0.008)	(0.008)	(0.008)
Q5&2012	-0.118***	-0.031**	-0.030**	-0.022*	-0.025*
	(0.010)	(0.011)	(0.011)	(0.011)	(0.011)
Q5&2015-16	-0.033***	-0.016	-0.015	-0.007	-0.014
	(0.009)	(0.010)	(0.010)	(0.010)	(0.010)
Q5&2017-18	-0.017+	0.005	0.006	0.007	0.005
	(0.010)	(0.011)	(0.011)	(0.010)	(0.010)
Reference = 2012 Survey					
2015-16		0.071***	0.070***	0.072***	0.076***
		(0.005)	(0.005)	(0.005)	(0.005)
2017-18		0.065***	0.064***	0.067***	0.068***
		(0.005)	(0.005)	(0.005)	(0.005)
2019-20		0.087***	0.086***	0.095***	0.097***
		(0.005)	(0.005)	(0.005)	(0.005)
Num. Obs.	58817	58817	58817	58817	58817
Controls	No	No	Yes	Yes	Yes
R^2 Adj.	0.004	0.010	0.011	0.087	0.110

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Q5 is income quintile five. Column (3) has economic controls: the inverse hyperbolic sine transformation of income, along with a binary variable for receipt of welfare benefits. Column (4) also has the dwelling and occupant controls (tenure type, dwelling structure, number of bedrooms, number of people and age quintiles). Column (5) also has the location controls (state and area).

In the case of Brazil, Table 11 indicates that the PV uptake probability in households in the 5th quintile increased by 4.6 percentage points between 2016 and 2022 (see the Q5&2016 coefficient in the first column). However, the uptake probability in households not in the fifth quintile increased by only 0.8 percentage points in the same period (see the 2022 coefficient in the second column). Therefore, the change in the PV uptake probability was 3.8 percentage points higher for Q5 than in the other quintiles (see the Q5&2016 coefficient in the second column). This result suggests an increase in the PV inequality from 2016 to 2022 in Brazil. Similar results were also found when adding control variables.

Table 11 - Pooled regression coefficients from linear probability models explaining solar panel uptake in Brazil; explanatory variables added progressively in each regression

	(1)	(2)	(3)	(4)	(5)
Reference = Q5&2022					
Not Q5	-0.057***	-0.051***	-0.047***	-0.047***	-0.046***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q5&2016	-0.046***	-0.038***	-0.038***	-0.038***	-0.038***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q5&2017	-0.045***	-0.037***	-0.037***	-0.037***	-0.037***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q5&2018	-0.040***	-0.034***	-0.034***	-0.034***	-0.034***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q5&2019	-0.036***	-0.030***	-0.030***	-0.030***	-0.030***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Reference = 2016 Survey					
2017		0.000	0.000	0.000	0.000
		(0.000)	(0.000)	(0.000)	(0.000)
2018		0.001**	0.001**	0.001**	0.001**
		(0.000)	(0.000)	(0.000)	(0.000)
2019		0.002***	0.002***	0.002***	0.002***
		(0.000)	(0.000)	(0.000)	(0.000)
2022		0.008***	0.007***	0.007***	0.007***
		(0.000)	(0.000)	(0.000)	(0.000)
Controls	No	No	Yes	Yes	Yes
Num. Obs.	730768	730768	730768	730768	730768
R^2 Adj.	0.015	0.016	0.017	0.020	0.022

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Q5 is income quintile five. Column (3) has economic controls: the inverse hyperbolic sine transformation of income, along with a binary variable for receipt of welfare benefits. Column (4) also has the dwelling and occupant controls (tenure type, dwelling structure, number of bedrooms, number of people and age quintiles). Column (5) also has the location controls (state and area).

Next, Table 12 and Table 13 provide more details on the relative adoption improvement by each income quintile. For example, the negative and significant coefficients in the first column mean that the increase in the rooftop PV uptake probability in the first quintile was less than the average increase in the other quintiles. Meanwhile, the coefficients for quintiles two to four are not significant in Australia, meaning that their relative situations have not changed over time. Finally, the fifth quintile shows improvement in its relative position after 2012.

Table 12 - Pooled ordinary least squares (linear probability models); separate income quintiles - Australia

	x = 1	x = 2	x = 3	x = 4	x = 5
Reference = Qx&2012					
Qx&2015-16	-0.024*	-0.007	0.014	0.008	0.011
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Qx&2017-18	-0.036***	-0.014	0.008	0.013	0.030**
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Qx&2019-20	-0.037***	-0.007	0.007	0.010	0.025*
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Num. Obs.	58817	58817	58817	58817	58817
Controls	Yes	Yes	Yes	Yes	Yes
R^2 Adj.	0.112	0.110	0.110	0.110	0.110

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Qx is income quintile x, where x varies across the five columns. The full control set is used, including the survey wave variable, as in Table 10 - column (5).

In the case of Brazil, the PV uptake probability in quintiles one to four seems to have grown less than in quintile five from 2016 to 2022. Quintile five has positive and significant coefficients, suggesting that the uptake probability in this group increased above the average rates for the other quintiles.

Table 13 - Pooled ordinary least squares (linear probability models); separate income quintiles - Brazil

	x = 1	x = 2	x = 3	x = 4	x = 5
Reference = Qx&2016					
Qx&2017	0.000	0.000	-0.001	0.000	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Qx&2018	0.000	-0.002*	-0.001	-0.001	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Qx&2019	-0.002+	-0.003***	-0.002**	-0.001	0.008***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Qx&2022	-0.015***	-0.014***	-0.008***	-0.001+	0.038***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Controls	Yes	Yes	Yes	Yes	Yes
Num. Obs.	730768	730768	730768	730768	730768
R^2 Adj.	0.016	0.016	0.015	0.016	0.022

	x = 1	x = 2	x = 3	x = 4	x = 5

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Qx is income quintile x, where x varies across the five columns. The full control set is used, including the survey wave variable, as in Table 11 - column (5).

3.4.4 Robustness analyses

First, as explained in section 3.2, we have used three approaches to examine the inequality in the adoption of residential PV systems in both countries. The three approaches led to similar conclusions: The inequality in the residential PV adoption in Australia and in Brazil has not changed substantially, especially in relation to low-income groups. Regarding the regressions, we also added weights to the LPM, resulting in similar results (see the supplementary R code – Appendix D). Logit and Probit models were also performed, confirming the inequality in the PV adoption over time in both countries. Additionally, we use several unshown control variables in the regressions. In Table 10 and Table 11, for instance, results remained significant while progressively adding controls. We further explored an alternative specification for Equation 2, substituting categorical income and age variables with continuous ones. Specifically, the income quintile categories were replaced by the inverse hyperbolic sine transformation of income. This alternative model reaffirmed the positive relationship between income and the probability of PV adoption. However, as anticipated, the results for Australia were less pronounced and significant than those for Brazil, attributable to the better distribution of PV systems in the former.

3.5 Discussion

Based on three methodological approaches, our analysis reveals the presence of persistent inequality in the residential PV adoption in Australia and in Brazil, particularly in relation to low-income groups. From 2012 to 2020 in Australia and from 2016 to 2022 in Brazil, only small changes in the distribution of solar systems among income quintiles were seen. However, Australia is in a better equality position than Brazil (the former with a Solar Gini of 0.14 and the latter of 0.61). In Australia, the issue is more pronounced in the first quintile, which remains lagging behind the other quintiles. On the other hand, in Brazil the disparity in PV adoption is more pronounced, notably affecting quintiles one to four in comparison to the fifth quintile. These findings hold even after controlling for other socioeconomic variables in the regression models.

Our results regarding Australia are corroborated by other studies (Best; Chareunsy; Taylor, 2023a, 2023b), however using wealth instead of income as the main economic variable. While these studies argue that wealth is a better economic metric to target solar policies, we argue that income is also a valid and convenient metric to work with. This is due to the higher data availability (see the Brazilian case, for example) and the ease of implementing policies based on income thresholds. In fact, historically, income has been utilized as an eligibility criterion for subsidy programs in numerous countries. This is exemplified in Australia and Brazil (Section 2) and in the United States as demonstrated by Paulos et al. (2021). Our findings for Brazil align with those presented by de Freitas (2022), demonstrating a diminishing influence of income on PV adoption in Brazil from 2013 to 2019. However, it is noteworthy that de Freitas's study utilizes a census tract level of analysis and does not investigate adoption patterns across the income distribution. In this context, our study reveals a deepening inequality in PV adoption for quintiles one and two in Brazil, experiencing a joint participation reduction from 13% to 10% between 2016 and 2022.

Our review of each country’s characteristics and policy background provides insights into the observed results. Compared to Brazil, Australia exhibits several factors that likely contribute to a more equitable distribution of PV systems: (i) a higher GNI per capita; (ii) lower levels of economic inequality; (iii) lower interest rates; (iv) higher levels of education; (v) capital subsidies; and (vi) a longer history of incentives promoting PV adoption. This argument is supported by Alipour et al. (2020), who identify education, income, and financial incentives that lower purchasing costs as key determinants of household PV adoption.

As shown in Appendix C Table 17, the per capita income of the fifth quintile in Brazil is just above the threshold for the first quintile in Australia. This helps to explain why quintiles one to four in Brazil are lagging behind in PV adoption. However, higher income levels alone do not fully account for Australia’s lower PV inequality. In fact, in countries with similar GNI per capita, such as England/Wales and the United States, PV inequality is comparable to that observed in Brazil (Borenstein; Davis, 2016; Grover; Daniels, 2017). Thus, Australia’s relatively low PV inequality may be attributed to its high overall level of PV penetration – nearly 30% of households, as shown in Table 6. Indeed, some scholars argue that technological diffusion is the key driver in promoting greater equity in PV adoption (O’Shaughnessy; Kim; Darghouth, 2023).

However, despite the relatively low PV inequality in Australia compared to Brazil and other developed countries, our findings suggest that technology diffusion alone may be insufficient to eliminate inequality in PV access for low-income groups. In both Australia and

Brazil, PV adoption in the first quintile has remained underrepresented and mostly unchanged over the past decade. Research indicates that PV inequality is driven by a range of factors, including low home ownership rates (Darghouth et al., 2022), difficulties in accessing financing, lack of information, housing-related structural issues (Heeter et al., 2021), limited power hosting capacity (Hartvigsson; Nyholm; Johnsson, 2023), and the absence of PV installation companies in less affluent neighborhoods (O'Shaughnessy et al., 2021). Furthermore, we emphasize that both Brazil (and to a lesser extent, Australia) provide subsidies on energy bills for low-income consumers. This results in a lower perceived electricity cost, which in turn reduces the incentive for these consumers to invest in PV systems.

Consequently, given the persistent PV inequality observed in both Australia and Brazil, as well as the multiple factors influencing it, we argue that a multifaceted approach is necessary to reduce these disparities. First, targeted policies remain essential for improving access to PV for lower-income groups. One alternative is to replace existing electricity subsidies for low-income consumers with direct subsidies for the installation of PV systems in their homes. This policy approach has been proposed for Brazil by Sermarini et al. (2024) and was tested on a limited number of households in Australia (APVI, 2023). Second, community solar programs can help address barriers such as low home ownership rates and housing-related structural challenges, which are particularly prevalent in low-income communities. Additionally, as noted by Konzen et al. (2024), such incentives should be developed alongside educational campaigns to raise public awareness of these programs.

Addressing PV inequality is not only a matter of egalitarian ethics and democratic principles but is also crucial for reducing the regressive effects of solar incentives (Konzen; Best; De Castro, 2024), the risk of energy poverty (Hammerle; Burke, 2022) and increasing per capita disposable income (Zhang et al., 2020), thereby improving the living conditions of vulnerable households. In this regard, capital subsidies, such as the SRES implemented in Australia, have proven to be effective mechanisms for promoting PV adoption (Best; Chareunsy; Li, 2021). However, our comparison of countries suggests that energy policies alone may not be sufficient to resolve PV inequality, particularly in developing nations. A country's socioeconomic conditions also play a significant role in shaping the distribution of PV systems within its society, indicating that deeper, structural changes are necessary to achieve a more equitable distribution of PV.

3.5.1 Limitations and future research

While our study presents compelling evidence for both countries, it is important to acknowledge certain limitations in comparing these cases. Specifically, our research examined the evolution of PV inequality separately for each country. This approach was aligned with our objective to understand how inequality in the adoption of grid-connected residential photovoltaic (PV) systems has evolved in Australia and Brazil. These findings, along with the country profiles and literature review, supported our discussion of the disparities between the two countries. However, it is crucial to recognize that our methods were not designed to directly address the causes of these disparities. For instance, integrating both countries into a single regression model could be a valuable direction for future research aimed at identifying causal factors. A comparative analysis with other countries boasting more prevalent solar markets may also offer valuable insights into the remarkably low Solar Gini observed in Australia. In this context, we posit that the Solar Gini index proposed in this study serves as a valuable tool for tracking the evolution of PV inequality across diverse contexts.

Additionally, both Brazil and Australia have recently introduced incentive policies specifically targeting low-income households for solar adoption. Given the recent nature of these policies, their impacts were not captured in our study. Further examination and analysis of these policies will contribute to a deeper understanding of their effectiveness. In fact, a promising avenue for future research involves integrating the findings of this essay with impact assessments. This will help dissect the effects of unequal PV penetration and the associated costs of subsidies across different income groups. Comparable studies conducted in Australia in the early 2010s (Nelson; Simshauser; Kelley, 2011; Nelson; Simshauser; Nelson, 2012), provide a precedent, albeit under different subsidy levels. In the case of Brazil, such research remains unexplored, presenting an opportune avenue for exploration.

3.6 Conclusion and policy implications

As the deployment of distributed solar energy proliferates globally, it becomes imperative to closely examine emerging energy injustices stemming from this facet of the energy transition. The pursuit of equality in PV access is not only ethically sound but also holds the potential to enhance the quality of life, foster economic development, and accelerate the energy transition. By employing three distinct analytical approaches, our study underscores that the inequality in residential PV adoption in both Australia and Brazil exists and has not changed substantially over the years. Notably, lower-income quintiles consistently exhibit a significantly lower probability of adoption compared to their higher-income counterparts.

Our comparative analysis highlights both the differences and similarities between two distinct countries, contributing to a broader understanding of a just energy transition. Australia, for example, holds a relatively superior position, characterized by a more equitable distribution of solar systems across income groups. Our quantitative findings, combined with country profiles and a review of the literature, suggest that this outcome may be attributed to the long-term availability of capital subsidies alongside more favorable socioeconomic conditions. Despite the differences between the two countries, our study demonstrates that the underrepresentation of low-income quintiles in PV adoption is a shared challenge. This suggests that technological diffusion alone may not be sufficient to close the PV adoption gap between the lowest income quintile and the rest of the population. Consequently, general policies aimed at incentivizing overall market development may demonstrate limited effectiveness in mitigating this inequality.

Considering the numerous barriers faced by low-income households in adopting PV, we argue that a multi-dimensional approach is essential to address these disparities. First, targeted policies play a crucial role in advancing justice in solar access. If governments use income to determine eligibility for policy support, then specific thresholds could help to target support to households who are more likely to struggle to afford solar panels. In Australia, the bottom quintile based on household income have been less likely to obtain solar panels. In Brazil, solar-panel uptake by the highest income quintile has been substantially above uptake for the lower four quintiles, motivating broader support across these four quintiles. Secondly, community solar programs can help overcome obstacles like low homeownership rates and housing-related structural issues, which are especially common in low-income communities. Moreover, these incentives should be complemented by educational campaigns to increase public awareness of the programs.

Our study offers a distinct contribution to the energy justice framework. In the realm of distributional justice, we demonstrate that the likelihood of solar adoption among low-income groups has shown minimal improvement over the past decade. From a cosmopolitan perspective on energy justice, our findings suggest that, given the socioeconomic challenges faced by developing economies, achieving a more equitable distribution of PV systems in these countries may require additional efforts that go beyond adjustments to energy policies.

4 THIRD ESSAY: FROM NET-METERING TO NET-BILLING: EVALUATING THE TARIFF EFFECTS OF DISTRIBUTED GENERATION IN BRAZIL

ABSTRACT

Distributed generation (DG) has played a central role in the expansion of the Brazilian electricity grid, accounting for approximately 10% of the regulated market of electricity distributors. However, this growing penetration raises concerns about tariff impacts and energy justice. In an effort to reduce subsidies for DG in Brazil, a transition has been implemented from the original net-metering model to the net-billing model, which is set to fully take effect in 2029. However, the tariff effects of this new compensation model, particularly for low-income consumers, are not well understood. Using an adaptation of the official regulatory methodology, it was found that net-billing will reduce subsidies but will not eliminate tariff impacts. Projections indicate that a 35% penetration of DG will increase tariffs by 8%, and for low-income consumers by 6%, in median terms. Additionally, advancements in storage could amplify this effect. These findings underscore the need for comprehensive solutions that go beyond revising the compensation model for DG. The adoption of multi-part tariffs is recommended, separating fixed and variable costs, particularly considering the potential liberalization of Brazil's electricity market, which could allow all consumers to choose their energy suppliers. The implications of these results extend to other countries that predominantly use volumetric tariffs, highlighting the importance of a well-designed regulatory framework to balance incentives and economic impacts in the electricity sector.

Keywords: Tariff; Net-metering; Solar Energy; Distributed generation; Energy justice

4.1 Introduction

The decentralization of energy systems has become a global trend, particularly with the widespread adoption of distributed generation (DG) systems. In this context, a new actor has emerged in the energy sector: the prosumer, a consumer who actively participates in energy production. This paradigm shift is transforming energy infrastructure and necessitating regulatory and market reforms to integrate such resources in a fair and efficient manner. Polycentric governance is considered essential for facilitating decentralization by enabling contextualization, experimentation, and innovation (Goldthau, 2014). In this context, concerns about energy justice are increasing (Heffron, 2022), particularly regarding inequalities in access to DG systems and the regressive effects of policies designed to promote this form of generation.

Indeed, the literature provides robust evidence of cross-subsidies in DG incentive policies and their distributive effects. Studies highlight the challenge of recovering fixed costs in the electricity sector and the need for electricity tariff increases to compensate for market reductions (Eid et al., 2014b; Kubli, 2018; Küfeoğlu; Pollitt, 2019; Picciariello et al., 2015). In a systematic review, Konzen et al. (2024) identified that the integration of DG exhibits regressive characteristics. In other words, the costs of incentive policies are passed on to electricity tariffs, disproportionately burdening low-income households. In this context, several countries have begun adopting an incentive model known as net billing to reduce subsidies and make DG expansion more sustainable. According to IRENA (2019), net-billing "is a market-based compensation mechanism, as prosumer compensation is based on the actual market value of the kilowatt-hours (kWh) consumed or injected into the grid".

Brazil followed the trend observed in other countries. In 2012, DG was initially regulated by ANEEL through Normative Resolution No. 482/2012 (REN 482), allowing any consumer to generate their own electricity. Additionally, the resolution established the net metering model, which enabled surplus energy to be exported to the distribution grid, generating electricity credits (kWh) that could be used within 60 months. In other words, the value of surplus energy was equivalent to the full electricity tariff. In 2022, Law No. 14,300 was enacted, establishing the legal framework for DG in Brazil, aiming to provide greater legal stability to the sector and reduce DG subsidies. Consequently, a slow and gradual transition to the net billing model was introduced, which will be fully implemented by 2029.

Despite changes in the compensation model, investments in solar DG remain highly attractive in Brazil, making it the leading source of newly added capacity in the country. By the end of 2024, more than 3 million DG systems were connected to the grid, totaling an installed capacity of approximately 36 GW (ANEEL, 2025d). However, this expansion is not evenly distributed across society. Nearly 70% of residential installations are concentrated in households within the highest income quintile, while the lowest income quintile accounts for only 3% of installations. Moreover, little progress has been made in distribution over the years. Between 2016 and 2022, there was a slight improvement among intermediate income groups, whereas the two lowest quintiles lost share during this period (Konzen; Best; De Castro, 2025). This issue is exacerbated by the characteristics of the compensation model implemented in Brazil. By generating their own electricity, prosumers avoid paying most of the costs associated with the use of transmission and distribution systems, as well as sectorial charges. Since the electricity tariff is determined by the ratio between the required distribution revenue and the billed market, these costs are ultimately covered by other consumers through tariff increases (Eid et al., 2014b). In fact, the Brazilian Electricity Regulatory Agency (ANEEL) estimates that in 2024, distributed generators received a total subsidy of R$ 11.6 billion (approximately US$ 2 billion) (ANEEL, 2025a).

Law No. 14,300/2022 introduced changes aimed at reducing subsidies for DG in Brazil while preserving benefits for early investors. The original incentive model will remain in effect until 2045 for those who submitted a DG system connection request to the distribution utility before early 2023 (classified as DG I). From 2023 onward, new generators (classified as DG II or DG III, depending on power capacity) will gradually receive lower compensation for energy injected into the grid to account for distribution network usage. Finally, starting in 2029, surplus generation will be valued based solely on the energy component, along with an additional amount reflecting the benefits of DG to the electricity system. Following IRENA's (2019) definition, the model in place from 2029 onward is classified as a net billing scheme, as surplus energy will be compensated based on its actual value to the system.

Therefore, starting in 2029, one group of generators (DG II and III) will face a reduction in subsidies, while another group (DG I) will continue to receive the benefit until 2045. In parallel, the share of self-consumption (part of generation not exported to the grid) by both groups will also influence the cost recovery of the power sector and, consequently, tariffs. Additionally, the way subsidies are allocated within tariffs varies depending on the consumer class. For example, the tariff for low-income households is exempt from certain costs, including the subsidy for distributed generation. As a result, there is a combination of factors that need to be quantified in order to understand the final impact on consumers.

Several authors have studied the recent changes in Brazil's DG compensation model and its tariff effects, but with a focus limited to the transition period of the compensation model. Martins et al. (2022), Iglesias and Vilaça (2022), and da Silva and Rato (2024) identified that the transition rule brought improvements over REN 482, but cross-subsidies still persist. Proposed solutions include the use of binomial tariffs, the revision of compensated tariff components, and the implementation of a subsidy cap. On the other hand, the study by Leite et al. (2024) focused solely on analyzing the impact of the new legal framework for DG in Brazil on investment attractiveness. The authors concluded that, even with the reduction of subsidies, the internal rates of return for DG investments will remain attractive.

Therefore, the existing literature does not provide a comprehensive analysis of the tariff impacts of the net-billing model, which is scheduled to come into effect in Brazil starting in 2029. In this context, this study aims to address this gap, specifically with the following enhancements to the existing literature: (i) the methodology approved by ANEEL for tariff calculation is employed, ensuring greater rigor in the analysis; (ii) both historical impacts (net-metering) and future impacts are analyzed, considering the new net-billing model; (iii) a distinct analysis of tariffs for conventional consumers and low-income consumers is conducted, highlighting aspects related to energy justice; (iv) the methodology is applied to 32 distribution companies, covering 90% of the country's consumers. Although the focus of this study is on Brazil, the results are expected to be relevant for other countries transitioning to the net-billing model.

Section 2 provides an overview of the regulatory framework, covering tariff regulation model and the distributed generation incentive policy in Brazil, as well as the effects of their interaction. The research methodology is presented in Section 3, explaining how the tariff calculation process was adapted to capture the effects of the integration of distributed generation. Section 4 presents the main results. A discussion of the results in relation to the existing literature is provided in Section 5, along with the limitations and opportunities for future research. The final section presents the conclusions and policy implications.

4.2 Overview of tariff regulation and distributed generation incentives in Brazil

The impacts of the integration of distributed generation (DG) on electricity tariffs largely depend on the degree of DG penetration in the market, the existing incentive and subsidy policies, and the structure of tariff regulation in the country. In this regard, this section aims to provide an overview of the tariff structure and compensation models in Brazil, as well as explore the economic and tariff implications of these changes.

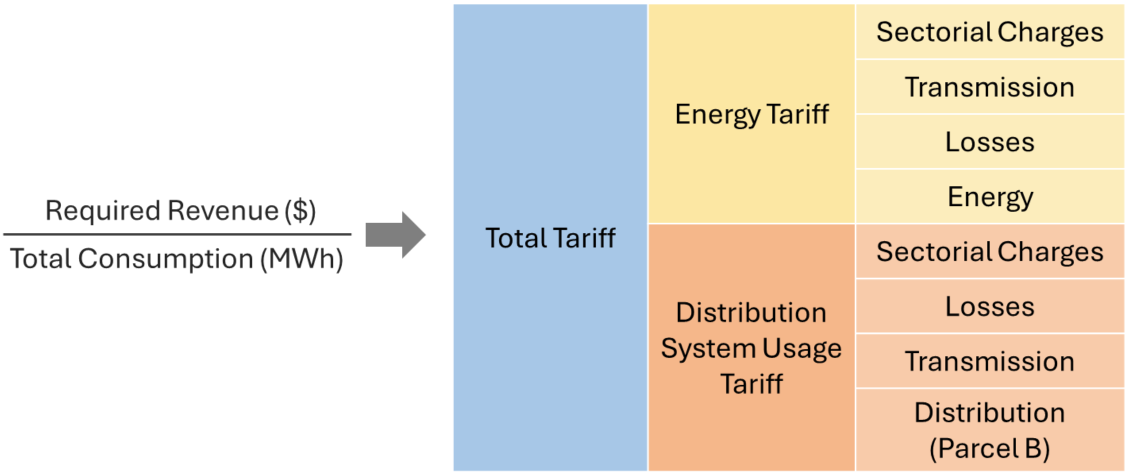
4.2.1 Tariff regulation model in Brazil

The tariff definition process aims to calculate the regulatory revenue needed to cover the total costs of the electricity sector. For calculation purposes, these costs are divided into two parts. Parcel A includes costs that are beyond the control of the distribution company, such as energy acquisition costs, transmission costs, and sectorial charges. These costs are directly passed on to consumers (pass-through). Parcel B includes costs associated with the provision of distribution services, aiming to remunerate investments made by the distribution company and cover operational and administrative costs (Brandão et al., 2021).

Each year, ANEEL conducts a tariff adjustment process — a simplified procedure for updating tariffs. Every four to five years, a tariff review process takes place, which is a more detailed procedure for tariff definition. For example, during the tariff adjustment, Parcel B is updated based on inflation and a distribution efficiency factor (ANEEL, 2024a). In contrast, during the review process, the costs of Parcel B, such as distribution investments and O&M costs, are examined in detail (ANEEL, 2024b). Regarding Parcel A, the procedure is similar for both the review and adjustment processes. These costs are projected by the regulator for the next 12 months and incorporated into the new tariff. Additionally, any forecasting errors are compensated in the subsequent tariff (Brandão et al., 2021).

After defining the regulatory revenue, the regulator breaks it down into components that form the Distribution System Usage Tariff (TUSD) and the Energy Tariff (TE) (ANEEL, 2019a). The sum of these two components equals the final tariff applied to consumers. Figure 12 illustrates the tariff components.

Figure 12 - Electricity Tariff Components in Brazil



Note: Taxes are not considered. Tax application occurs afterward and is not part of ANEEL's tariff-setting process. Source: Adapted from ANEEL (2019a).

The calculation of tariff components considers the voltage level at which consumers are served and the tariff modality. However, tariffs applied to low-voltage (LV) consumers are entirely volumetric. In other words, the final bill amount is proportionally dependent on the monthly energy consumption of the consumer unit ($/kWh). Time-of-Use (ToU) tariffs are optional for LV consumers. However, only 0.1% of consumers have adopted this tariff modality (ANEEL, 2025b). The majority of consumers pay a flat tariff.

In addition to the conventional tariff applied to most consumers, there is the Social Electricity Tariff (TSEE), which is granted to low-income consumers. The TSEE is lower because it excludes certain electricity sector charges, such as explicit subsidies for distributed generation (BRASIL, 2002). Additionally, beneficiaries of the TSEE receive a progressive discount on their electricity bill, up to a limit of 220 kWh/month, effectively making it an increasing-block volumetric tariff from the consumer's perspective. According to ANEEL, 17 million consumers (approximately 20% of the total) benefit from this program. However, the Agency estimates that 7.7 million consumers are eligible for the discount but do not receive it. This is due to registration issues, irregular connections, or lack of electricity access in their households (ANEEL, 2024c).

4.2.2 The energy compensation model in Brazil

In 2012, Brazil regulated distributed microgeneration and mini generation (DG) through ANEEL's Normative Resolution No. 482/2012 (REN 482). This resolution allowed any regulated consumer to install a DG system based on renewable sources or qualified cogeneration and connect it in parallel with the distribution grid. Additionally, the net metering mechanism was introduced, enabling consumers to inject excess energy into the grid in exchange for credits (ANEEL, 2012). As a result, consumers were allowed to generate their own electricity, thereby reducing their electricity expenses.

Subsequently, Normative Resolution No. 687/2015 (REN 687) introduced modifications to REN 482. The power limit was expanded from 1 MW to 5 MW, and the credit compensation period was extended from 36 to 60 months. Additionally, two new compensation modalities were established: generation for multiple consumer units and shared generation. Both modalities allowed a generating system to generate credits for multiple consumers, either locally or remotely, respectively (ANEEL, 2015).

In 2022, Federal Law No. 14,300/2022 (BRASIL, 2022) was enacted, establishing the legal framework for distributed microgeneration and mini generation. Regarding the compensation scheme, full tariff compensation (net metering) was guaranteed until 2045 for existing generators and those who submitted an access request to the distribution company by January 7, 2023. This group was later classified by ANEEL's REN No. 1,059/2023 as DG I. For generators that requested access after the mentioned date (classified as DG II or DG III depending on the system size), a partial compensation model applies. In these cases, energy credits can only compensate for a portion of the tariff, as indicated in Table 14.

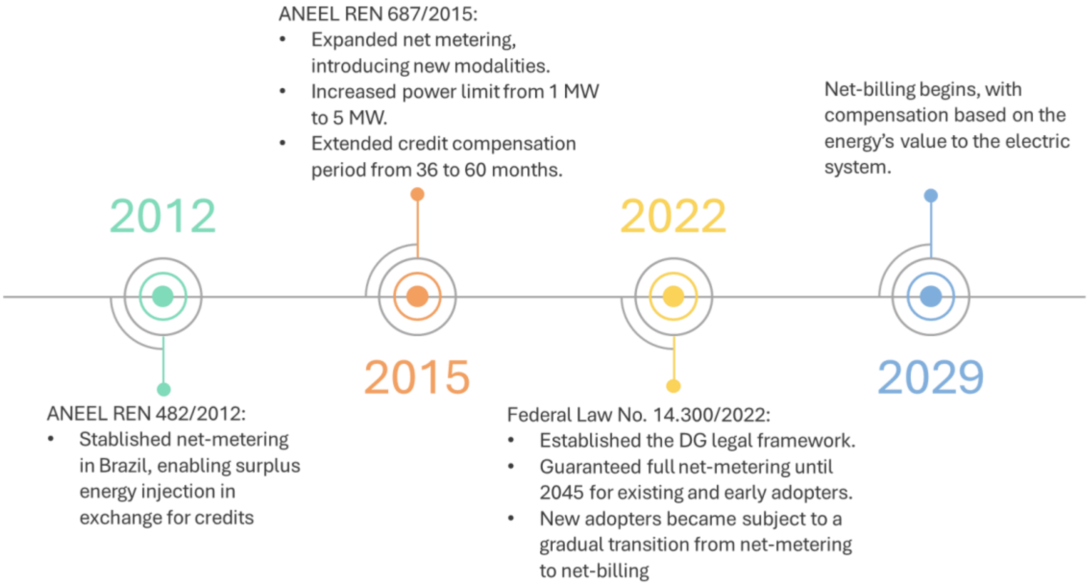
Table 14 - Non-energy costs charged to different categories of prosumers

Year	DG I	DG II	DG III
2023	No charge	15% of distribution costs	100% of distribution costs + 40% of transmission costs + 100% of R&D and inspection charges
2024		30% of distribution costs	
2025		45% of distribution costs	
2026		60% of distribution costs	
2027		75% of distribution costs	
2028		90% of distribution costs	
2029+		All non-energy costs minus benefits (net-billing)	All non-energy costs minus benefits (net-billing)

Note: DG I refers to systems that requested access to the grid by January 7, 2023. DG II includes systems that requested access after January 7, 2023. DG III comprises off-site photovoltaic systems above 500 kW that requested access after January 7, 2023. Source: BRASIL (2022)

Starting in 2029, as shown in Table 14, all costs not related to energy will be charged to prosumers in groups DG II and III. However, these costs may be reduced if the benefits of integrating distributed generation (DG) into the grid exceed the costs. According to Law No. 14,300/2022, this calculation "should consider all benefits, including the locational benefits of DG to the electrical system, covering generation, electrical losses, transmission, and distribution components." Therefore, this model aims to remunerate the excess generation injected into the grid according to its real value to the electrical system. Thus, following the definition provided by IRENA (2019), the compensation model that will come into effect in Brazil in 2029 can be classified as net-billing. Figure 13 illustrates the evolution of the energy compensation model for distributed generation in Brazil, based on regulatory milestones.

Figure 13 - Evolution of the Compensation Model for Distributed Generation in Brazil



ANEEL REN 687/2015:
- Expanded net metering, introducing new modalities.
- Increased power limit from 1 MW to 5 MW.
- Extended credit compensation period from 36 to 60 months.

Net-billing begins, with compensation based on the energy's value to the electric system.

ANEEL REN 482/2012:
- Stablished net-metering in Brazil, enabling surplus energy injection in exchange for credits

Federal Law No. 14.300/2022:
- Established the DG legal framework.
- Guaranteed full net-metering until 2045 for existing and early adopters.
- New adopters became subject to a gradual transition from net-metering to net-billing

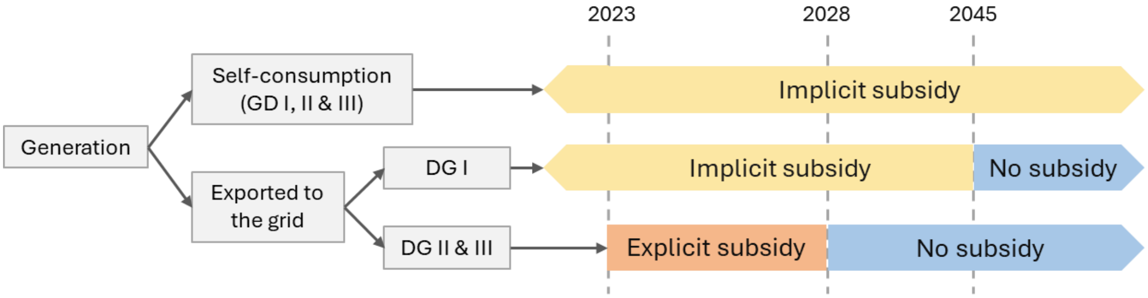
Source: Own elaboration.

4.2.3 Tariff Impacts of the Energy Compensation Model in Brazil

As explained by the Brazilian regulator (ANEEL, 2019a), the cost of purchasing energy is proportionally dependent on the distributor's market. Therefore, with the increase in distributed generation, there is a market reduction and a proportional decrease in this cost. On the other hand, some costs are not dependent on the volume of energy consumed. These are pre-defined costs related to investments in transmission and distribution infrastructure, as well as the charges that cover subsidies for the electric sector. Thus, they are fixed costs in the short term. Consequently, a reduction in the market, due to the increase in distributed generation, results in: "i) a decrease in the total regulatory revenue, due to the reduction of revenues dependent on market variables; and, ii) an increase in the average tariff, since some fixed costs do not decrease with the reduction in the market." (ANEEL, 2019a). Indeed, this effect is not exclusive to the Brazilian market, as it has been reported internationally by other authors (Eid et al., 2014b; Picciariello et al., 2015).

Therefore, a distributed generator, by using the energy credits injected to offset tariff components unrelated to the cost of energy, fails to remunerate certain fixed costs of the sector. In this context, Law No. 14,300/2022 defined that for DG II and III, these unremunerated components will be covered by the Energy Development Account (CDE) until 2028 as an explicit subsidy. However, as argued by ANEEL (2022), this remuneration through the CDE did not represent a new cost to consumers. Implicitly, due to the market reduction, tariffs already accounted for this cost during tariff-setting processes. Additionally, Law No. 14,300/2022 excluded DG I costs from being covered by the CDE, and thus, these costs will continue to be implicitly incorporated into tariffs until 2045. Finally, it should be noted that a portion of the generation is consumed instantaneously by the prosumer and is not exported to the grid. This portion (called self-consumption) also causes a market reduction and an increase in tariffs.

Figure 14 - Energy flow from distributed generation systems and timeline of subsidies



Source: Own elaboration.

Figure 14 summarizes the timeline of subsidies for distributed generation in Brazil. The category of the projects (DG I, II, or III) defines how subsidies are considered in electricity tariffs. Another relevant factor for the analysis is the self-consumption ratio (SCR), which indicates the percentage of generation that is consumed instantaneously. In Brazil, a study by EPE (2023f) indicated an average SCR of 34% for the residential sector. However, this factor varies according to the generation and consumption profile. Internationally, authors have identified residential SCR between 37% and 45% (McKenna; Pless; Darby, 2018; Stridh, 2020). Additionally, storage strategies and demand-side management (DSM) can be used to increase this ratio. Studies show that a battery system can increase residential SCR by 13 to 24 percentage points, while DSM can increase it by 2 to 15 percentage points (Luthander et al., 2015). With the reduction of the remuneration on energy exported to the grid, it is likely that there will be increased interest in solutions to enhance the SCR of solar systems installed in Brazil, thereby altering the tariff dynamics in the country.

4.3 Methodology

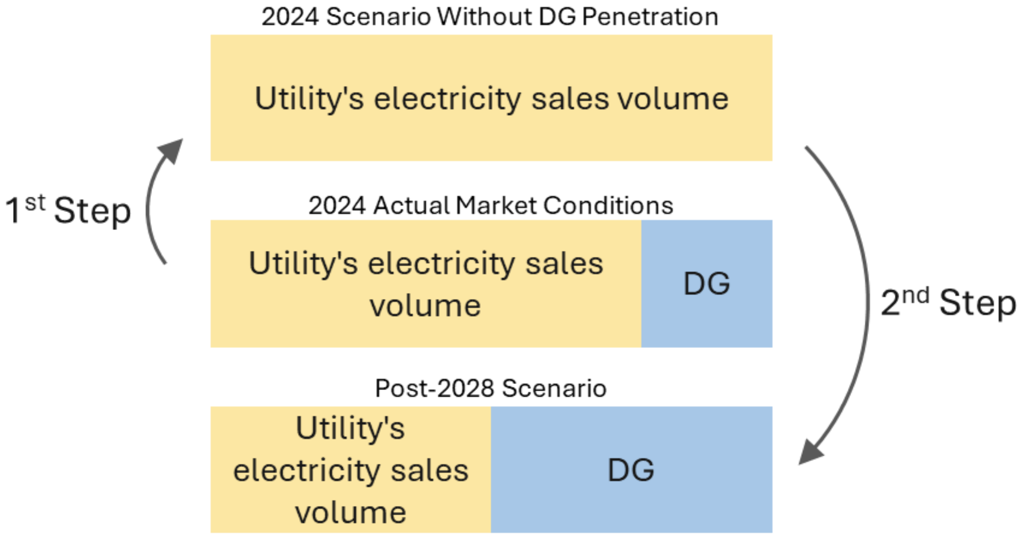
Firstly, it is important to emphasize that the study aims to assess the impact of distributed generation (DG) integration on tariffs, with a particular focus on the consumer. Therefore, the issues are not addressed from the perspective of distribution companies, particularly the revenue shortfall and exposure to new risks arising from the DG compensation model. Other studies have analyzed the distributors' perspective in Brazil and complement the present analysis (Da Silva; Rato, 2024; Iglesias; Vilaça, 2022; Martins; Branco; Hallack, 2022).

In order to estimate the tariff impact of the integration of distributed generation (DG) in Brazil, the calculation used by the Brazilian regulator (ANEEL) during tariff processes was replicated. The calculation is done with spreadsheets in MS Excel, publicly available from the regulator in each tariff adjustment or review process (ANEEL, *[S.d.]*). The "PCAT" spreadsheets for the year 2024 were used, with the modification of parameters to simulate the integration of DG and assess its effect on the final tariffs of each distributor. This approach is based on a study by ANEEL (2019a). In addition to calculating conventional tariffs, the spreadsheets also calculate tariffs for low-income consumers, which are important for the scope of this study. The analysis covers 32 distributors in Brazil, representing 90% of the national regulated consumption. Small distributors (those with an electricity market of less than 700 GWh/year) were excluded from the analysis as they are subject to distinct rules for tariff calculation – including how DG subsidies are incorporated. Additionally, four distributors (CPFL PIRATININGA, EDP ES, EQUATORIAL PI, CEEE) could not be analyzed due to issues in reading the available spreadsheets.

In order to simulate the effect of the penetration of DG, the analysis was carried out in two steps, as presented below. Figure 15 illustrates the steps executed.

a) First step: simulate the tariffs in a scenario without distributed generation (0% penetration). Starting from the 2024 situation in each distributor, the effects of the existing DG were simulated to be removed, and a corresponding increase in the electricity market was assumed. This step allows for simulating the historical tariff impact up to 2024. That is, it estimates what the tariffs applied to consumers would be if there were no DG and no compensation system.
b) Second step: based on the results from the previous step, the inverse process was carried out, simulating higher DG penetration percentages (up to 50% of regulated market). This second step simulates the tariff impact after 2028 (and before 2045), that is, after the transition rules for DG II and DG III come into effect.

Figure 15 - Illustration of the two-step methodology: the first step models the 2024 electricity market without DG penetration, while the second step simulates a scenario with higher DG penetration after 2028



Source: Own elaboration.

In order to obtain the energy contribution from DG in 2024, an estimate provided by the Energy Research Company (EPE) based on the 4MD model (EPE, 2024) was used. The use of this estimate is necessary because the total energy generated by prosumers is not measured by the distributors. Therefore, the calculation methodology takes into account factors such as the installed capacity of DG, solar radiation levels, Performance Ratio, degradation of photovoltaic modules, among other parameters (EPE, 2023e). The EPE estimate also categorizes the generation into DG I and DG II, which is essential to differentiate the subsidies for each type of generation. To simulate higher levels of DG penetration, the existing DG I generation was maintained, and DG II was added until the desired penetration percentage was reached. This approach is justified because the classification of DG I was used for projects installed until early 2023.

It is important to note that the impact analyzed is limited to electricity tariffs, expressed in $/MWh. The final impact on consumer bills depends on other variables that were not evaluated in this study, such as the effect of taxes, additional discounts for the Low-Income class, and tariff flags.

The main modifications made in the spreadsheets are explained below, and a record of all the changes can be found in the supplementary R code (Appendix D).

4.3.1 Energy market size

The penetration of distributed generation reduces the electricity market size of the distributors – the amount of energy the distributors need to purchase to supply their consumers. Therefore, in the first step, to nullify the effects of DG, the total energy generated from DG connections in the 12 months prior to the tariff process was added to the market considered in each distributor's tariff process. In this way, a hypothetical situation is created where all electricity consumption would be purchased from the distributor, with no impact from the DG compensation scheme. As a result, there is an increase in the market size, leading to an increase in the total regulatory cost associated with purchasing energy from the distributor. Additionally, to avoid double-counting, the compensated DG energy that was originally included in the spreadsheet was excluded.

In the second step, the inverse process was performed, reducing the distributor's electricity market according to the simulated penetration of DG (see Figure 15). As a result, there is a decrease in the company's total market and a reduction in the total regulatory cost.

To simplify the simulation process, all estimated distributed generation was allocated to the low-voltage market of the distributor. This is an approximation, as energy compensation by high-voltage consumers represents a small portion of the total. In fact, data from ANEEL indicate that only 9% of the energy compensated in 2024 was by high-voltage consumers (ANEEL, 2025e). This occurs because even projects connected to high voltage mostly allocate their credits to low-voltage consumers. Additionally, consumers served by high voltage have accelerated their migration to the "Free Electricity Market (CCEE, 2025)". As the DG compensation model in Brazil is valid only for regulated consumers, the adoption of DG by high-voltage consumers is expected to decrease in the future.

4.3.2 Technical and Non-Technical Losses in Distribution

The reduction in network consumption tends to reduce electrical losses. In fact, this is a benefit considered in most cost-benefit evaluations of DG (DSouza et al., 2021). In this regard, a linear reduction in losses was considered in relation to the penetration of DG. However, this is a conservative assumption, as depending on the level of penetration and the location of DG, there may be an increase in electrical losses (Adefarati; Bansal, 2016). In addition to technical losses in distribution, it is assumed that the penetration of DG reduces non-technical losses (theft or fraud). These assumptions are part of the procedure approved by the regulator for the tariff calculation, which defines regulatory percentages for losses to be considered in the tariff process. Therefore, variations in the market directly affect costs related to technical and non-technical losses. Thus, the analysis reflects the reality of the tariff calculation in Brazil. In summary, in the first step, there is an increase in regulatory costs related to losses, while in the second step, there is a reduction.

4.3.3 Distribution costs

As discussed in Section 2.1, the tariff adjustment and revision processes differ in the definition of Parcel B, with the former applying a parametric calculation formula, while the latter involves a more detailed cost analysis. Since the tariff revision year is not uniform, to prevent the 2024 tariff revision schedule from influencing the results, the same approach was applied to all distribution companies. In this regard, the calculation based on the tariff adjustment process was considered, where the variation of Parcel B is proportional to market variation.

It is assumed that a larger market size requires higher operational and capital costs in electricity distribution activities. On the other hand, the greater the penetration of DG, the smaller the market size and the lower the distribution costs. This premise is debatable, as the literature points to differing conclusions. While some authors find that DG integration can bring economic benefits by deferring investments in distribution (Cohen; Kauzmann; Callaway, 2016), others suggest that DG can increase costs by requiring new investments in transformers and cables (De Souza Almeida Neto et al., 2023). Despite this discussion, this is the procedure used by ANEEL for tariff calculation. Equation 4 shows how the updated distribution cost ($Dcost_1$) is calculated. This equation is based on the parametric formula found in electricity distribution concession contracts in Brazil, where in tariff adjustment processes, the regulatory cost of the distribution service is updated by market variation, inflation, and efficiency gains.

$$Dcost_1 = Dcost_0 \pm DG \cdot Dtariff \cdot (1 + IGPM + XFactor) \tag{4}$$

The original distribution cost is represented by $Dcost_0$. In the scenario without DG (first step), this cost is increased by the additional volume of electricity that would be sold by the distribution company if there were no distributed generation. In this case, DG represents the volume of distributed generation in 2024. This volume is multiplied by the current distribution tariff (*Dtariff*), updated by the inflation index (*IGPM*) and the distributor's efficiency index (*XFactor*).

Symmetrically, in the second step, $Dcost_0$ is reduced (see the negative sign) as distributed generation penetration occurs. However, in the second step, only the contribution of the DG I and self-consumption DG II components is considered. This modeling is applied because the effect of the injected DG II component is already accounted for in another category, as explained in Section 3.4.

The ANEEL database was used to obtain the value of the tariff component related to distribution costs (*Dtariff*) for each distributor (ANEEL, 2025c). The effects of efficiency gains during the period were disregarded (*XFactor* equal to zero), and an inflation rate of 3% per year was assumed, which is the center of the target set by the National Monetary Council (2024).

4.3.4 Explicit Subsidies to Distributed Generation

As explained in Section 2.2, starting in 2023, part of the non-energy-related costs that are not remunerated by prosumers is transferred to other consumers through an explicit subsidy. This subsidy is calculated by the regulator and included in the tariff calculation spreadsheets as an additional cost to the CDE. Therefore, the scenario without DG penetration (first step) is simulated by setting this item to zero.

Starting in 2029, prosumers in the DG II group will begin paying all non-energy-related components. In this case (second step), the payment tariff is multiplied by DG II injected into the grid. This amount is considered as a reduction in the required revenue for the distributor, helping to reduce the tariff, as it represents an amount to be recovered by the DG II prosumers. Prosumers of the DG I group will continue receiving the benefit of full compensation (all tariff components) until 2045. However, this subsidy is not part of an explicit category – therefore, its effect is accounted for as a market reduction (as explained in section 3.1).

4.3.5 Additional tariff components

It is assumed that costs related to the transmission network and other sectorial charges are not changed by the integration of distributed generation. Thus, these are considered fixed costs in this study. Although distributed generation may defer investments in transmission, this effect varies depending on the location of the generators, the network topology, and the network's power flows (Luo et al., 2014). In fact, a study by EPE identified the opposite effect, the need to increase transmission investments in a specific region of Brazil due to the high penetration of DG in that region (EPE, 2023d). In any case, transmission costs have a low impact on the total costs of the electricity sector, representing about 8% of the residential tariff (ANEEL, 2025c). Therefore, given the uncertainty regarding the impact of DG on transmission, and its relatively low representation in total costs, it is assumed that these costs remain unchanged with DG penetration. Similarly, costs related to sectorial charges that are unaffected by DG penetration (e.g., the Light for All Program, subsidies for coal, irrigation subsidies, the Incentive Program for Alternative Energy Sources – Proinfa, among others) are also considered unchanged.

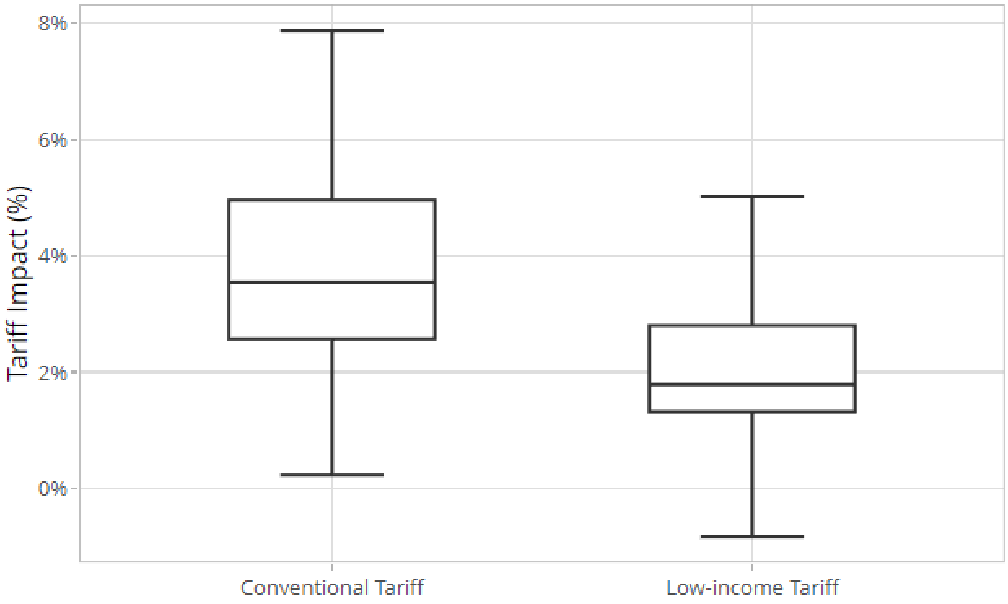
4.4 Results

This section highlights the main findings of the study. The complete results can be accessed through an interactive web application available at the following link: https://lookatthedata.shinyapps.io/dgimpacts/.

4.4.1 Historical impacts on tariffs

As initial results, the estimated tariff impact up to the 2024 tariff process for each distributor is presented. This historical percentage impact is the ratio of the 2024 tariff approved by ANEEL to the simulated tariff without DG penetration. Figure 16 shows an approximate median increase of 3.5% for conventional tariffs and 1.8% for low-income tariffs. However, a significant variation in impact is observed, with increases reaching up to 8% for conventional tariffs and 5% for low-income consumers, depending on the distributor.

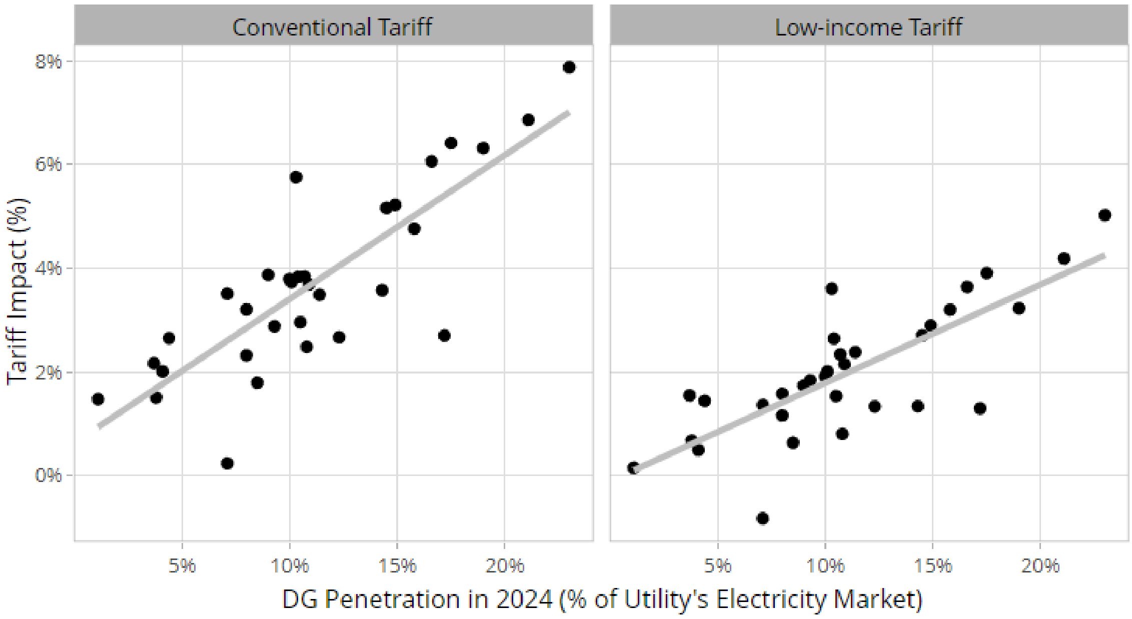
Figure 16 - Effect of DG Penetration on Electricity Tariffs Across Utilities: Impact on 2024 tariffs relative to a scenario without DG penetration



Source: Own elaboration.

The variation in the results can be explained by several factors, such as the cost structure of the distributor and the percentage of DG penetration at the time of the tariff calculation. Figure 17 shows the positive relationship between DG penetration and the effect on tariffs. In fact, the two variables exhibit a correlation close to 80% in both data sets. Despite the correlation between the two variables, it is noteworthy that the effect of DG penetration on low-income tariffs is smaller. The lower slope of the regression line, compared to the case of conventional tariffs, indicates that the increase is proportionally smaller for the same level of DG penetration. This is mainly explained by the non-incidence of sectorial charges such as CDE on low-income tariffs (including the component for funding the DG subsidy) and Proinfa (BRASIL, 2010). Additionally, it is important to highlight the distinct realities across the country. At one extreme, Enel SP has 1% of its regulated consumption from DG, while at the other extreme, Energisa MS has a penetration of 23%.

Figure 17 - Tariff impact as a function of DG penetration, relative to the 0% DG penetration scenario. The DG penetration level represents the actual percentage for the year 2024.



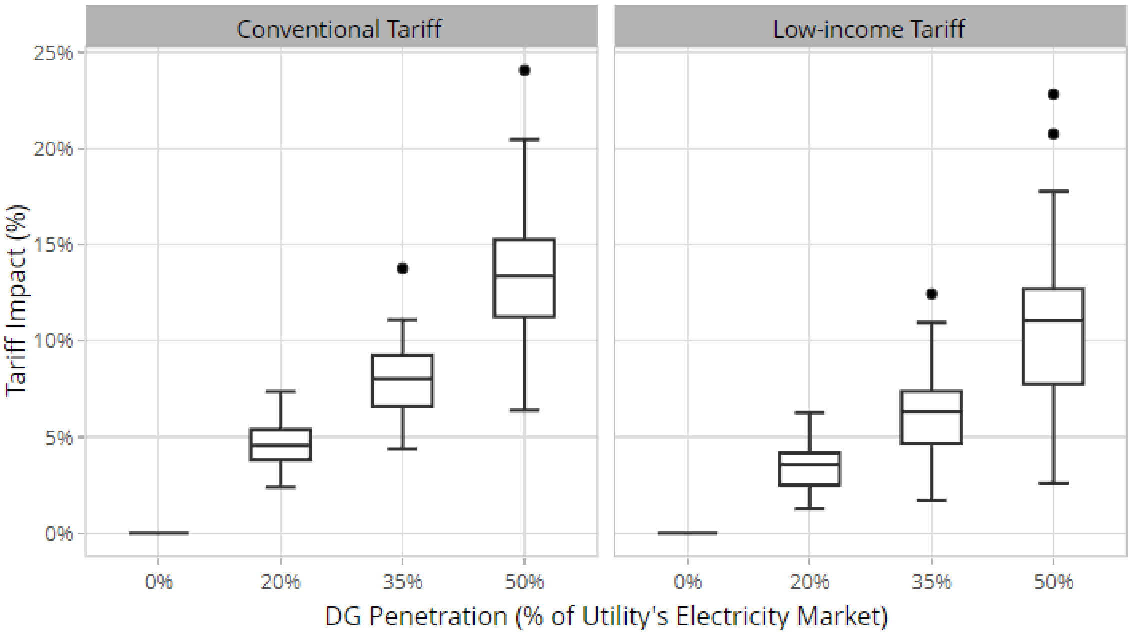
Note: The points represent each of the distributors analyzed. The lines are linear regressions based on the points.
Source: Own elaboration.

4.4.2 Post-2028 projected impacts on tariffs (under net-billing)

As presented in Section 2.3, starting in 2029, there will be a change in the dynamics of subsidies to DG in Brazil. Specifically, projects classified as DG II and DG III (installed after 2022) will be subject to the net-billing model, paying for all tariff components except for the energy component. However, this charge only applies to credits generated from the energy injected into the grid. The portion of the generation that is self-consumed will remain exempt from any charge, which impacts the recovery of fixed costs in the electricity sector. In this context, this section analyzes the tariff effects post-2028.

As an initial analysis, the distribution of the tariff impact among all the simulated distributors is evaluated. Figure 18 shows the results assuming a self-consumption ratio (SCR) of 40%. A trend for tariff increases is observed as DG penetration increases. Despite the variation observed, all distributors experience tariff increases. Regarding the Low-Income class, it is noticeable that the effect is slightly smaller than that observed for the conventional class, although the trend of tariff increase remains as DG penetration increases.

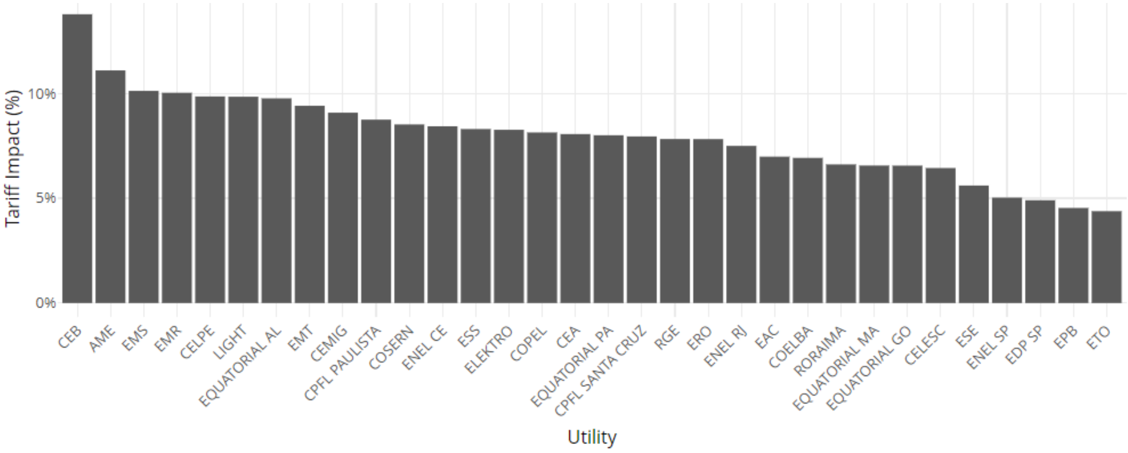
Figure 18 - Effect of DG penetration on electricity tariffs across utilities by tariff class, relative to the scenario with 0% DG penetration. The analysis assumes a self-consumption ratio of 40%.



Source: Own elaboration.

In an individual analysis (Figure 19), it is identified that the distributor CEB will experience the highest positive tariff increase, while ETO will have the smallest impact on the conventional tariff, given the assumptions of a 40% SCR and 35% DG penetration. Several factors explain this difference, such as the cost structure of the distributor, the percentage of free and regulated consumers, and the distribution of consumers among the consumption classes in each distributor.

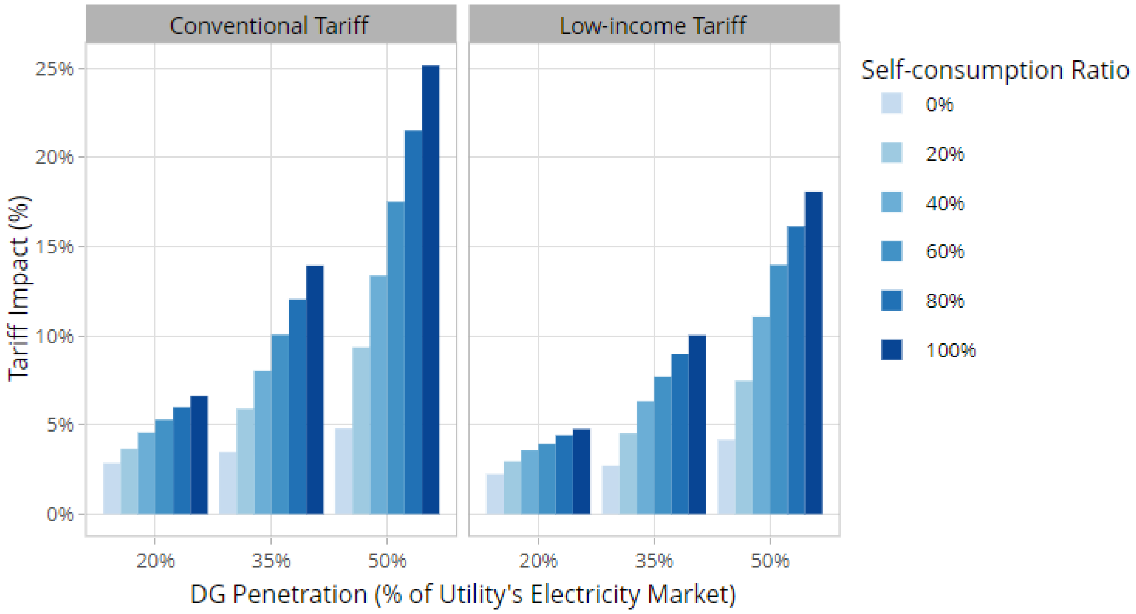
Figure 19 - Effect of DG penetration on conventional electricity tariffs across utilities, relative to the 0% DG penetration scenario. This analysis assumes a DG penetration level of 35% and a self-consumption ratio of 40%.



Source: Own elaboration.

It is important to emphasize that a sensitive aspect of the results is the SCR considered. As discussed in Section 2.3, this ratio varies according to the consumer and can be increased with the introduction of storage systems or demand-side management mechanisms. As Figure 20 shows, the higher the self-consumption, the greater the increase on the tariff. This happens because self-consumed generation reduces the payment of all tariff components, including those that cover fixed costs. On the other hand, the portion injected into the grid will, starting in 2029, only offset the energy component, meaning that a portion of the generation will no longer be subsidized. The result demonstrated reflects the combination of these two opposing effects.

Figure 20 - Median tariff impact of DG self-consumption relative to the 0% DG penetration scenario. The bars show the median impact across all electricity distribution utilities.

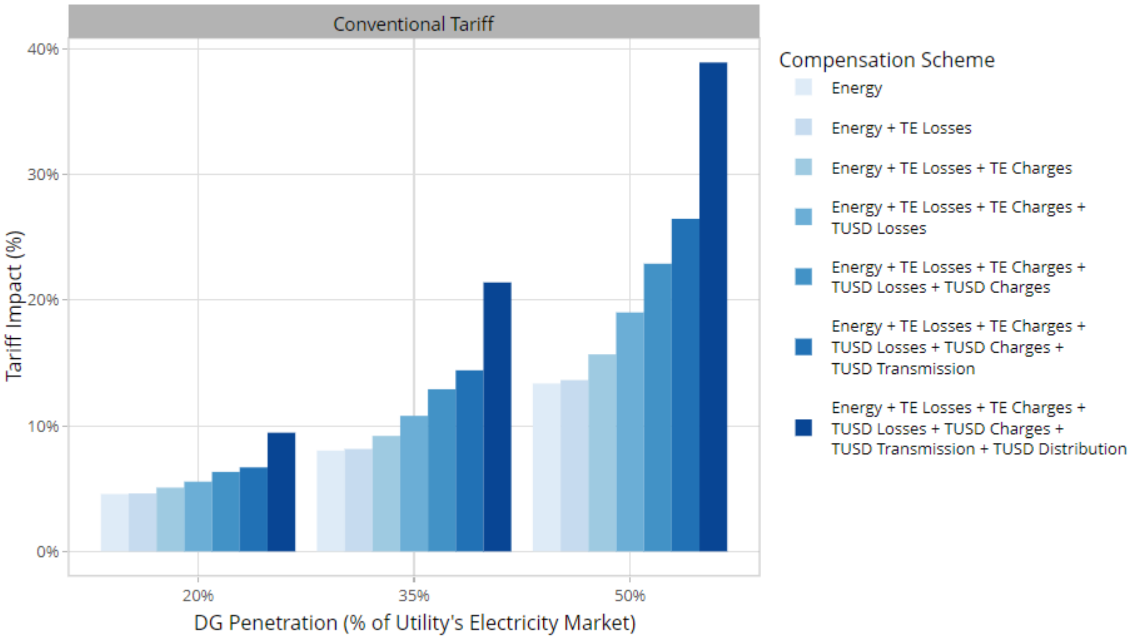


Source: Own elaboration.

4.5 Projection of impacts with alternative compensation models

As presented in Section 2, starting in 2029, with the introduction of the net-billing model, a reduction in subsidies for projects classified as DG II or DG III is expected. According to Law No. 14,300/2022, the energy injected into the grid will only offset the energy component of the tariff. This compensation model was used as a reference in the previous analyses. However, as an additional sensitivity, the result of a possible change in the compensation model starting in 2029 was simulated. In this section, different levels of subsidy are considered, varying according to the tariff components used in the compensation. The objective of this analysis is: (i) to understand the tariff impact in Brazil if Law No. 14,300/2022 did not implement the removal of subsidies; and (ii) to understand the effect of a new legal change aimed at reinstating the subsidized model – a request from part of the society.

Figure 21 - Median tariff impact of the compensation scheme relative to the 0% DG penetration scenario. The bars show the median impact across all electricity distribution utilities



Source: Own elaboration.

Figure 21 indicates the effect of the compensation model on tariffs as DG penetration increases. The reference case, used in the previous analyses, is shown in the lightest color (compensation only for the energy component). If Brazil had maintained the original net-metering model, with compensation for all tariff components (dark blue in the graph), the median impact on tariffs would be close to 40% in a scenario where distributed generation had a 50% penetration of the electricity market. Therefore, this analysis indicates that the change introduced by Law No. 14,300/2022 was significant in reducing the tariff impact of distributed generation insertion. Additionally, returning to a subsidy model like the previous one could significantly affect the electricity bills of consumers who do not adopt distributed generation.

4.6 Discussion

Through a simulation of the tariff adjustment process for 32 electricity distribution companies in Brazil, this study identified the impact of distributed generation (DG) penetration on electricity tariffs. It is estimated that DG insertion has led to a median increase of 3.5% in conventional residential tariffs by 2024. However, this effect varies between 0% and 8%, depending on the distribution company. This variation can be explained, among other factors, by the level of DG penetration in each concession area. The study demonstrated a high positive correlation between these two variables. In general, the greater the DG penetration, the higher the tariff impact. As a reference, the median DG penetration in Brazil is 10% of the regulated market. In addition to the historical impact up to 2024, the study also simulated the tariff impact after 2028, when the net billing model will take effect. This analysis showed that the compensation model based only on the energy component (as planned from 2029 onwards) will continue to exert upward pressure on tariffs, leading to increases proportional to the level of DG penetration. A penetration level of 50%, for instance, would result in a median increase of 13% in electricity tariffs. On the other hand, if no changes had been made to the compensation model, the increase could reach 40%. Therefore, while net billing can mitigate the impact of DG penetration on tariffs, it does not eliminate it.

An important aspect of the study's findings concerns the self-consumption rate of distributed generation. With the reduction in the remuneration for the energy injected into the grid (as planned from 2029 onward), prosumers will have greater incentives to increase self-consumption. This can be achieved through energy storage systems or demand-side management strategies, for example. In fact, this trend has been observed in countries that have reduced subsidies for solar energy. More than 60% of solar systems installed in Germany and Italy in 2023, for instance, included a battery storage system (BloombergNEF, 2023). In this context, the study indicates that an increase in the self-consumption rate leads to a greater impact on electricity tariffs. This occurs because self-consumed generation offsets 100% of tariff components, whereas energy injected into the grid offsets only the energy component. Consequently, if the self-consumption rate of DG increases, prosumers will contribute less to the costs of the electricity sector, even with the adjustments introduced by Law No. 14,300/2022.

The findings are supported by studies that highlight the effects of cross-subsidization under the net metering regime with the expansion of distributed generation (Eid et al., 2014b; Picciariello et al., 2015; Sergici et al., 2019), as well as the potential "utility death spiral" effect (Castaneda et al., 2017). The net metering model has been shown to lead to a greater transfer of income from consumers to prosumers compared to the net-billing model, as indicated by Chen et al. (2023). On the other hand, da Silva and Rato (2024) argue that the net-billing model set to take effect in Brazil after 2029 is sustainable for both utilities and consumers. However, the present study indicates that electricity tariffs are likely to continue rising even under net-billing. Darghouth et al. (2016) suggest that an increase in DG penetration tends to lower wholesale energy prices at certain times, which, in turn, reduces the remuneration for surplus generation for consumers exposed to time-varying tariffs. According to the authors, this mechanism could help mitigate the utility death spiral. However, it is important to highlight that in Brazil, nearly all low-voltage consumers pay a flat volumetric tariff, and the current metering system lacks time-based or smart metering. As a result, the self-correcting effect identified by Darghouth et al. (2016) is unlikely to materialize in the Brazilian context.

One approach to mitigating the impact of DG on electricity tariffs is the adoption of multi-part tariffs, which typically include a volumetric component (based on consumption) and a fixed or demand-based component. This solution is supported by various studies on tariff models in the context of high DG penetration (Burger et al., 2019; Da Silva; Rato, 2024; Eid et al., 2014b; Farrell, 2021; Martins; Branco; Hallack, 2022; Strielkowski; Štreimikienė; Bilan, 2017). A more sophisticated alternative is proposed by Cambini and Soroush (2019), which incorporates an additional variable component to account for electrical loss costs, in addition to the fixed and volumetric components. Under this design, prosumers would initially pay a lower amount for grid usage due to their contribution to loss reduction. However, as DG penetration increases, network usage tariffs would rise to reflect the growing system losses. It is important to highlight that tariff design reform not only enhances efficiency in cost recovery for distribution utilities but also provides a more effective price signal for decision-making regarding the adoption of generation systems (Ros; Sai, 2023b).

4.6.1 Impact on Low-Income Consumers

An important aspect of this analysis is the distinction between conventional consumers and those benefiting from the Social Electricity Tariff (TSEE). The results indicate that the impact of DG penetration up to 2024 is approximately half of that observed for conventional consumers (1.8% versus 3.5%). However, post-2028 simulations with higher DG penetration suggest a narrowing of the impact difference between the two tariff categories. For instance, under a scenario with 35% DG penetration and 40% self-consumption, the median tariff impact for conventional consumers is 8%, while for TSEE consumers, it is 6%. Thus, making DG subsidies explicit in the CDE account and exempting TSEE consumers from this charge has not eliminated the impact of DG penetration on low-income consumers' electricity tariffs. A portion of these subsidies remains implicit in the tariff calculation, affecting all residential consumers indiscriminately.

It worth mentioning that the wealthiest 20% of Brazilian households own nearly 70% of residential solar systems, while the poorest 20% hold only 3% (Konzen; Best; De Castro, 2025). Additionally, electricity expenses consume four times more of the budget of lower-income families compared to wealthier households (Wilher, 2021). As a result, distributed generation primarily benefits higher-income families in Brazil, while the tariff increases driven by this policy impose a heavier financial burden on lower-income households. In this context, these findings contribute to the literature on energy justice. The results indicate that Brazil's DG incentive policy is flawed in terms of distributional justice – as defined in Suboticki et al. (2023) – by unequally distributing the burdens and benefits of solar energy.

4.6.2 Limitations and future research

First, it is important to highlight that certain methodological simplifications were adopted in calculating the tariff impact. As mentioned in Section 3, the analysis assumes that compensation for distributed generation occurs exclusively among low-voltage consumers. This assumption was made due to the difficulty in predicting the share of generation across voltage groups in the coming years. However, it is argued that the share of compensation in high voltage is currently below 10% and is expected to decline further, given the ongoing migration to the free electricity market.

Another important limitation concerns the way DG affects the costs of the electricity sector. Following the tariff adjustment process adopted by ANEEL, the analysis assumes a reduction in losses and distribution costs as the penetration of distributed generation increases. However, some studies suggest that these costs may rise instead of decrease (Adefarati; Bansal, 2016; De Souza Almeida Neto et al., 2023). Therefore, although the present study follows the methodology approved by ANEEL, future research could explore the effects of variations in specific cost components.

An additional limitation is that the estimation of impacts was based on a single tariff adjustment process (2024). Tariff adjustments are complex and interdependent over time, as there are mechanisms to adjust certain costs to avoid deficits or surpluses in distributors' revenues. These adjustments particularly affect transmission costs and sectoral charges, classified as Parcel A items. Since only the year 2024 was considered, variations in these adjustment components over the years were not accounted for. However, this approach is not expected to compromise the conclusions, as these adjustments represent less than 5% of the final consumer tariff.

This study was limited to assessing the effects of distributed generation penetration on electricity tariffs. The impact on the final consumer bill depends on additional elements such as taxes and other public policies (e.g., discounts for low-income consumers), which were not considered. Moreover, a broader impact assessment on society would require the inclusion of externalities, such as effects on industry, job creation, and environmental aspects. This type of comprehensive analysis is suggested for future research.

Finally, although the literature recommends the use of multi-part tariffs to address high distributed generation penetration, the effect of this tariff structure was not modeled. This decision was based on the difficulty of obtaining data relevant to the Brazilian context, such as typical values for injection and consumption demand in households with DG systems. Therefore, incorporating this aspect into future studies could provide further support for decision-making in Brazil.

4.7 Conclusion and policy implications

The decentralization of energy systems is advancing worldwide. In Brazil, specifically, distributed generation of electricity (DG) leads the addition of capacity to the electricity grid in recent years. In fact, the energy contribution of this modality is already significant. It is estimated that approximately 10% of the electricity consumption in the Brazilian regulated electricity is market in Brazil is meet through DG. In this context, concerns regarding the impacts of existing incentive policies are growing, particularly in relation to the sustainability of these policies and energy justice.

By adapting the methodology used by the Brazilian regulator, it was identified that the penetration of DG until 2024 increased residential electricity tariffs by 3.5%, on a median basis. With the changes introduced by Law No. 14.300/2022, Brazil implemented a gradual reduction in subsidies for DG. Thus, starting in 2029, excess energy injected into the grid will be compensated only for the value of the energy itself (with an additional amount for benefits to the electric system). Therefore, a shift from a net-metering model to a net-billing model is characterized in Brazil. However, the study shows that the change in the compensation model will reduce the impact of DG insertion on electricity tariffs but will not eliminate it. The higher the penetration of DG, the higher the expected tariff increase. A 35% penetration, for example, leads to a median increase of 8%. It is shown that this impact could be even higher if there is a movement to increase the share of self-consumption of generation – for example, through storage systems. This trend is expected, given the reduction in the remuneration for excess energy exported to the grid.

The study also showed that tariffs for low-income consumers are slightly less impacted by the introduction of DG compared to conventional tariffs. A 35% penetration of DG, for example, would lead to a median increase of 6% in tariffs for low-income consumers.

Therefore, the incentive policy for DG in Brazil has not only failed to bring the benefits of solar energy to the most vulnerable households (Konzen; Best; De Castro, 2025), but also transfers the costs of this policy to them.

Therefore, the study shows that partial solutions, such as Law No. 14,300, which only addressed the compensation mechanism, do not structurally solve complex problems such as those in the distribution sector. Specifically, the transition from net-metering to net-billing models needs to ideally be accompanied by a tariff reform, with the introduction of multi-part tariffs to make the recovery of electricity sector costs sustainable. In the Brazilian context, the adoption of multi-part tariffs is of additional importance, given the movement towards opening the free electricity market in the country. The Ministry of Mines and Energy intends to allow all consumers to choose their electricity supplier (MME, 2022b), highlighting the need to design a tariff structure that separates fixed costs, primarily related to transmission and distribution services, from variable costs, mainly energy.

It is important to note that the study focused on the impacts on consumers. However, there is a broader discussion about the role of distribution companies under the new paradigm of integrating distributed energy resources. This discussion goes beyond the tariff model, involving the revision of the compensation model for distribution companies, reconsideration of the structure of the electricity sector to avoid conflicts of interest, and improvements in electricity markets (Pérez-Arriaga; Jenkins; Batlle, 2017). Therefore, it is understood that joint solutions are the ideal approach. Finally, it is emphasized that the findings not only contribute to the regulatory debate in Brazil but also offer relevant insights for other countries facing similar challenges in integrating distributed generation.

5 CONCLUSIONS

The decentralization of power systems and the expansion of distributed photovoltaic generation (DG) have emerged as key features of the energy transition toward decarbonization. Despite the notable growth and associated benefits of this generation modality, concerns have been raised regarding energy justice and equitable access to such technologies. Specifically, questions persist about how the costs and benefits of DG are distributed across different segments of society. In this context, the primary objective of this study is to evaluate whether the expansion of distributed electricity generation aligns with the principles of energy justice, with a particular focus on the Brazilian case. More specifically, this study investigates whether there is evidence of inequality in the adoption of residential DG systems and whether it tends to decrease over time. It also examines whether current DG incentive policies produce regressive distributional effects, disproportionately benefiting higher-income households. Additionally, the analysis explores the potential tariff impacts associated with the transition from the net-metering to the net-billing compensation model. Finally, the study aims to identify policy recommendations that could help reduce inequality in DG adoption and mitigate regressive impacts.

The results indicate that residential adoption of photovoltaic systems remains concentrated among high-income households, both in developed and developing countries. In Brazil, this disparity is particularly pronounced: the highest income quintile accounts for nearly 70% of installations, while the lower 40% hold less than 5% of systems. This pattern partially reflects the diffusion of innovations theory, whereby emerging technologies are initially adopted by privileged groups. However, even after 13 years of incentive policies, the democratization of DG in Brazil remains limited, revealing structural shortcomings. A comparison with Australia—where adoption is relatively more evenly distributed—suggests that long-term capital subsidies may help mitigate, though not eliminate, disparities. The stagnation of adoption among low-income groups in both countries indicates that mere technological diffusion is insufficient to overcome barriers such as high upfront costs, limited awareness of incentives, lack of access to financing, and low homeownership rates.

This dissertation also demonstrates that incentive policies for distributed generation (DG) often have regressive effects. In Brazil, the net-metering model introduced subsidies funded through tariff increases that are passed on to all consumers. The findings indicate that, up to 2024, the expansion of DG led to an estimated median increase of approximately 3.5% in conventional electricity tariffs and 1.8% in tariffs for low-income consumers. The transition to a net-billing system, as mandated by Law No. 14,300/2022, will partially reduce the subsidies. However, projections indicate that a 35% DG penetration rate will result in an 8% increase in conventional electricity tariffs and a 6% increase in tariffs for low-income consumers—disproportionately impacting vulnerable groups that devote a larger share of their income to energy expenditures. Furthermore, advances in energy storage technologies may exacerbate this effect by increasing the share of self-consumption, thereby reducing contributions to grid costs.

To address the distributional challenges identified across the three essays, this dissertation puts forward a set of converging and complementary policy recommendations.

i. First, comprehensive tariff reform is essential. The transition from net-metering to net-billing, as implemented through Law No. 14,300/2022 in Brazil, represents progress in correcting distortions in the compensation mechanism for DG. However, this measure alone is insufficient to ensure long-term tariff sustainability and fairness. A more structural reform, notably the adoption of multi-part tariffs that differentiate fixed and variable components, is necessary to align tariff structures with the evolving electricity system;

ii. Second, if policymakers choose to maintain subsidies for distributed generation, these should be explicitly targeted toward vulnerable groups. The continuation of subsidies must be conditioned on the use of clear income-based eligibility criteria. In addition, the promotion of community solar programs should be scaled up. Community solar can address multiple barriers simultaneously, including lack of roof space, homeownership, and access to credit;

iii. Third, educational and outreach campaigns are critical for ensuring inclusive participation in the energy transition. Low levels of information and awareness continue to hinder the participation of marginalized groups in DG programs. Public engagement initiatives should be tailored to reach low-income communities, using accessible language and channels;

iv. Fourth, the role of distribution companies must be redefined. As DG and other distributed energy resources become increasingly integrated into the power system, it is essential to rethink the responsibilities, incentives, and compensation models for distribution utilities. This includes revising regulatory frameworks to prevent conflicts of interest and support grid modernization, reliability, and innovation. New business models may be necessary to enable these actors to facilitate, rather than resist, the expansion of distributed resources;

v. Finally, it is acknowledged that technological diffusion alone is insufficient to ensure equitable access to solar energy. Especially in developing economies, the socioeconomic constraints faced by a large share of the population call for coordinated, multi-dimensional strategies that extend beyond energy policy. Addressing inequality in DG adoption may require integrated social, housing, tax, financial, and educational policies. Only through a broader commitment to distributive and procedural justice can the energy transition become both sustainable and inclusive.

This dissertation offers robust evidence of energy injustice in the diffusion of DG. For policymakers, it provides not only concrete recommendations to address these disparities but also an analytical framework for assessing the distributive impacts of DG-related policies. The incorporation of adoption inequality metrics and simulations of tariff impacts under varying DG penetration levels presents practical tools to inform policy decisions. The study challenges the prevailing assumption that market mechanisms alone will ensure broad-based access to DG and demonstrates how unequal outcomes can arise even in the presence of well-intentioned policies. Notably, the work underscores that energy justice should be treated as a central principle in public policy design rather than as a secondary consideration or a mere externality.

For researchers, the study contributes methodologically and conceptually to the growing field of energy justice. It bridges theoretical constructs with applied policy analysis and enhances the empirical literature on distributed energy resources in developing economies, contexts that remain underrepresented in global energy scholarship. By combining quantitative modeling with qualitative insights and cross-country comparisons, the dissertation exemplifies an interdisciplinary approach capable of capturing the multifaceted nature of energy inequality.

For society, the dissertation promotes a more inclusive vision of the energy transition. By foregrounding the experiences and constraints of low-income households, the work amplifies the voices of marginalized groups who are often excluded from energy planning and governance. Ultimately, it aspires to contribute to the construction of a more just and equitable society through a fairer energy transition.

Despite the significant contributions of this dissertation to the understanding of energy justice in the context of DG, several avenues remain open for future research to address the study's limitations and to further advance the field:

i. This analysis primarily focused on economic inequality, without addressing other critical dimensions of energy justice—such as procedural justice, which involves the right to meaningful participation in energy-related decisions and institutions. Other axes of inequality, including those related to race, also warrant further investigation;

ii. Although a shift to multi-part tariffs is recommended in the literature as a means of improving distributive outcomes in Brazil, this dissertation did not simulate the effects of such a reform due to methodological limitations. Future studies could fill this gap by assessing the potential impacts of tariff restructuring;

iii. Recent inclusion-oriented policies, such as the Brazilian Social Renewable Energy Program (PERS), offer promising ground for future evaluations regarding their effectiveness in reducing inequality in DG adoption;

iv. More comprehensive impact assessments are encouraged to evaluate the broader consequences of DG adoption. These may include externalities, implications for the expansion and maintenance of power grids and equipment, and wider economic effects on society;

v. Further studies could examine the impacts of DG adoption under different compensation schemes—such as net metering and net billing—which have received comparatively less attention in the literature than feed-in tariffs;

vi. There is a need for greater geographic diversity in the academic literature, as most existing studies are concentrated in developed economies. As this dissertation has highlighted, socioeconomic context is deeply intertwined with energy justice outcomes. Future research could further explore this relationship in underrepresented regions;

vii. Comparative cross-country analyses are also encouraged. While this dissertation made initial strides by comparing the cases of Australia and Brazil, the adopted methodology did not allow for a statistical identification of the causes behind observed differences. This remains an open question in the literature;

viii. Although this study examined the evolution of DG inequality over time, the analysis was limited to a period of less than a decade. Studies covering extended timeframes are recommended to better capture trends and long-term effects.

In summary, the findings reinforce that energy justice must be a central pillar in energy transition planning. Distributed solar energy is not merely a technical tool, but an opportunity to redefine social and economic relations within the electricity sector. To achieve this, it is essential that policy decisions prioritize inclusion, ensuring that the benefits of DG are broadly shared and that its costs are distributed fairly.

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7 APPENDIX A

Publications resulting from this dissertation:

KONZEN, G.; BEST, R.; DE CASTRO, N. J. The energy injustice of household solar energy: A systematic review of distributional disparities in residential rooftop solar adoption. Energy **Research & Social Science**, v. 111, p. 103473, 2024.

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KONZEN, G.; BEST, R.; DE CASTRO, N. J. Shining a light on disparities: A comparative analysis of residential photovoltaic adoption inequality in Australia and Brazil. **Energy Research and Social Science**, v. 119, 2025.

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8 APPENDIX B

Table 15 - List of papers reviewed

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Macintosh; Wilkinson, 2011)	2011	Australia	Postal Code	Distribution Charts	+	Increased	
(Nelson; Simshauser; Kelley, 2011)	2011	New South Wales (Australia)	Household	Distribution Charts, Electricity Market Model	+		Regressive
(Nelson; Simshauser; Nelson, 2012)	2012	Queensland (Australia)	General	Electricity Market Model			Regressive
(Kwan, 2012)	2012	US	Postal Code	Regression	+		
(McConnell et al., 2013)	2013	Australia	General	Electricity Market Model			Progressive
(Cludius et al., 2014)	2014	Germany	Not Applicable	Regression			Regressive
(Grösche; Schröder, 2014)	2014	Germany	Household	Correlation, Regression, Electricity Market Model, Inequality Metrics, Distribution Charts	+		Regressive
(Varela-Margolles; Onsted, 2014)	2014	Miami-Dade County - FL (US)	Census Tract	Survey/Interview, Distribution Charts	+		
(Griffith; Higgins; Turner, 2014)	2014	New Jersey and Massachusetts (US)	Postal Code	Cluster Analysis, Regression, Statistical Test	+		
(Graziano; Gillingham, 2015)	2015	Connecticut (US)	Census Tract	Regression	0		
(Andor; Frondel; Vance, 2015)	2015	Germany	Household	Regression	+		
(Frondel; Sommer; Vance, 2015)	2015	Germany	Household	Distribution Charts, Electricity Market Model			Regressive

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Schaffer; Brun, 2015)	2015	Germany	Region	Regression	+		
(Vasseur; Kemp, 2015)	2015	Netherlands	Household	Distribution Charts, Survey/Interview	+		
(Sigrin; Pless; Drury, 2015)	2015	San Diego County - CA (US)	Household	Survey/Interview, Statistical Test	+	0	
(Balta-Ozkan; Yildirim; Connor, 2015)	2015	United Kingdom	Region	Regression	0		
(Poruschi; Ambrey, 2016)	2016	Australia	Household	Regression	+		
(De Groote; Pepermans; Verboven, 2016)	2016	Flanders (Belgium)	Statistical Sectors	Regression	+	Decreased	
(Borenstein; Davis, 2016)	2016	US	Household	Distribution Charts, Inequality Metrics	+		
(Borenstein, 2017)	2017	California (US)	Household	Regression	+	Decreased	
(Grover; Daniels, 2017)	2017	England and Wales	Census Tract	Regression, Distribution Charts, Inequality Metrics	+		
(Böhringer; Landis; Angel Tovar Reaños, 2017)	2017	Germany	Household	General Equilibrium Model, Simulation			Regressive
(Dharshing, 2017)	2017	Germany	County	Regression	+		
(Többen, 2017)	2017	Germany	Region	General Equilibrium Model			Regressive
(Strielkowski; Štreimikienė; Bilan, 2017)	2017	Northern England	Household	Electricity Market Model			Regressive
(Vaishnav; Horner; Azevedo, 2017)	2017	US	Household	Cost-benefit Analysis	+	Decreased	
(Simpson; Clifton, 2017)	2017	Western Australia	Postal Code	Distribution Charts, Regression, Survey/Interview	-		
(Jayaweera; Jayasinghe; Weerasinghe, 2018)	2018	Colombo District (Sri Lanka)	Census Tract	Regression	+		

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Bernards; Morren; Slootweg, 2018)	2018	Netherlands	Postal Code	Regression	+		
(Yu et al., 2018)	2018	US	Census Tract	Correlation	+		
(Best; Burke; Nishitateno, 2019)	2019	Australia	Household	Regression	0 for income and for wealth"	0	
(Poruschi; Ambrey, 2019)	2019	Australia's Capital Cities	Postal Code	Regression	+		
(Lukanov; Krieger, 2019)	2019	California	Census Tract	Regression, Correlation	+	Decreased	
(Tidemann et al., 2019)	2019	Canberra (Australia)	Mesh Block	Distribution Charts, Regression	- for postcode and + for mesh block		
(Winter; Schlesewsky, 2019)	2019	Germany	Household	Inequality Metrics, Regression, Electricity Market Model	+		Regressive
(Araújo; Boucher; Aphale, 2019)	2019	New York (US)	Postal Code	Regression, Cluster Analysis	+		
(Strielkowski et al., 2019)	2019	Northern England	Regional	Electricity Market Model			Regressive
(Costa; Santos, 2020)	2020	Brazil	State	Correlation	+		
(Bennett et al., 2020)	2020	California (US)	Postal Code	Regression, Machine Learning	+		
(Bao et al., 2020)	2020	California and Massachusetts (US)	Household	Survey/Interview, Distribution Charts	+		
(Lekavičius et al., 2020)	2020	Lithuania	Household	Simulation	+		
(Fournier et al., 2020)	2020	Los Angeles County - CA (US)	Postal code	Correlation, Diffusion Model	+		

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Reames, 2020)	2020	Riverside and San Bernardino - CA, Washington - DC, Chicago - IL (US)	Census Tract	Regression, Statistical Test	+		
(Palm, 2020)	2020	Sweden	Municipality	Regression	-		
(Best; Chareunsy; Li, 2021)	2021	Australia	Household	Regression	+		
(Best; Nepal; Saba, 2021)	2021	Australia	Household	Regression	0 for income and + for wealth		
(Lan; Gou; Lu, 2021)	2021	Australia	Postal Code	Machine Learning	0		
(Irfan; Yadav; Shaw, 2021)	2021	India	Household	Regression	-		
(Copiello; Grillenzoni, 2021)	2021	Italy	Municipality	Time-series Analysis	-		
(Olczak et al., 2021)	2021	Poland	Province	Regression	-		
(Stewart, 2021)	2021	Scotland	Data-zones	Regression, Distribution Charts, Piecewise Structural Equation Modelling	- for community solar and + for household		
(Thompson et al., 2021)	2021	Southwest Nigeria	Household	Regression, Survey/Interview, Distribution Charts	+		
(Böhringer; García-Muros; González-Eguino, 2022)	2021	Spain	Household	General Equilibrium Model, Simulation			
(Farrell, 2021)	2021	United Kingdom	Household	Simulation			Regressive

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Keady et al., 2021)	2021	Vermont (US)	Household	Survey/Interview, Regression, Statistical Test	0		
(Wang et al., 2022)	2022	46 states (US)	Census tract	Diffusion Model, Regression	+		
(Best, 2022a)	2022	Australia	Household	Regression	+ (tenant)		
(Best; Chareunsy, 2022)	2022	Australia	Household/Aggregate	Distribution Charts, Regression	- to aggregate and + to household level		
(Feger; Pavanini; Radulescu, 2022)	2022	Bern (Switzerland)	Household	Structural Model, Regression	+		
(Alderete Peralta; Balta-Ozkan; Longhurst, 2022)	2022	Birmingham (England)	Postal Code	Diffusion Model, Regression	+		
(De Freitas, 2022)	2022	Brazil	Census Tract	Regression	+	Decreased	
(O'Shaughnessy, 2022)	2022	California and Connecticut (US)	Postal Code	Regression			
(Hansen; Jacobsen; Gram-Hanssen, 2022)	2022	Denmark	Household	Regression	+	0	
(Wicki; Pietrzykowski; Kusz, 2022)	2022	Poland	Region	Regression	+		
(Stewart, 2022)	2022	Scotland	Data-zones	Piecewise Structural Equation Modelling, Regression	+	Increased	
(Etongo; Naidu, 2022)	2022	Seychelles	Household	Regression	+		
(Aarakit et al., 2022)	2022	Uganda	Household	Regression	+		
(Best, 2022b)	2022	US	Household	Regression	+		
(Darghouth et al., 2022)	2022	US	Census Tract	Regression, Distribution Charts	+		
(Gao; Zhou, 2022)	2022	US	Census Tract	Regression	Recommendation		
(Shittu; Weigelt, 2022)	2022	US	Utility Area	Regression	+		

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Ros; Sai, 2023a)	2023	27 states (US)	State	Regression	+		
(Best; Chareunsy; Taylor, 2023b)	2023	Australia	Household	Distribution Charts, Regression	+	Increased	
(Best; Chareunsy; Taylor, 2023a)	2023	Australia	Household	Distribution Charts, Regression, LOWESS	+	0	
(Zhang et al., 2023)	2023	Australia	Postal Code	Regression, Cluster Analysis	-		
(Chueca et al., 2023)	2023	Brazil, Chile, Mexico	Household, Municipal, Regional	Regression		0	
(Kim et al., 2023)	2023	Colorado (US)	Census Tract	Neural Network, Machine Learning	+		
(Gunkel et al., 2023)	2023	Denmark	Household	Linear Optimization			
(Ruokamo et al., 2023)	2023	Finland	Household	Regression, Survey/Interview	+		
(Zhang; Ballas; Liu, 2023)	2023	Netherlands	Neighborhood	Regression	+		
(Khan; Ünel; Dvorkin, 2023)	2023	New York (US)	Postal Code	Single Leader Single Follower (SLSF) game			
(Min; Lee, 2023)	2023	Seattle, Bellevue, Portland (US)	Census Tract	Statistical Test, Cluster Analysis, Regression	0 for socioeconomic and + for house characteristics		
(Min; Lee; Hurvitz, 2023)	2023	Seattle, US	Census Tract	Statistical Test, Cluster Analysis, Regression	0 for socioeconomic and + for house characteristics		
(Kraaijvanger et al., 2023)	2023	The Hague (Netherlands)	Postal Code	Cluster Analysis	+		

Reference	Year	Location	Level of Analysis	Main Methods	Income Sign	Change in inequality over time	Type of impact
(Best; Esplin, 2023)	2023	US	Household	Regression	+ for wealth (home value) and 0 for income		
(O’Shaughnessy; Kim; Darghouth, 2023)	2023	US	Household	Distribution Charts, Diffusion Model	+	Decreased	
(Behnke; Shelton, 2024)	2024	Atlanta (US)	Household	Distribution Charts	+		

Note: (+) means a positive relationship between income (or similar metrics) and DGPV adoption; (-) means a negative relationship and (0) means that no significant statistical relationship was found by the study.

9 APPENDIX C

Table 16 - Descriptive statistics of dwellings in each survey

	Australia				Brazil				
Variable	2012	2015-16	2017-18	2019-20	2016	2017	2018	2019	2022
Solar panels	0.1 (0.3)	0.17 (0.38)	0.17 (0.38)	0.19 (0.39)	0 (0.07)	0.01 (0.07)	0.01 (0.08)	0.01 (0.09)	0.02 (0.14)
Monthly income (PPP)	4,184.68 (3,361.83)	4,503.87 (4,005.63)	4,890.04 (4,976.56)	5,360.14 (4,550.56)	1,474.03 (2,045.96)	1,513.86 (2,121.1)	1,575.71 (2,301.28)	1,595.54 (2,380.41)	1,718.4 (2,451.69)
Welfare	0.53 (0.5)	0.59 (0.49)	0.47 (0.5)	0.44 (0.5)	0.53 (0.5)	0.53 (0.5)	0.53 (0.5)	0.53 (0.5)	0.58 (0.49)
Bedrooms	3.09 (0.89)	3.1 (0.91)	3.12 (0.94)	3.08 (0.97)	1.84 (0.79)	1.83 (0.78)	1.81 (0.78)	1.8 (0.78)	1.79 (0.77)
People	2.44 (1.29)	2.35 (1.27)	2.38 (1.28)	2.39 (1.3)	3.03 (1.52)	3.01 (1.5)	2.97 (1.49)	2.94 (1.48)	2.84 (1.42)
University	0.35 (0.48)	0.37 (0.48)	0.39 (0.49)	0.41 (0.49)	0.11 (0.32)	0.12 (0.32)	0.13 (0.34)	0.13 (0.34)	0.15 (0.36)
Owned	0.68 (0.47)	0.68 (0.47)	0.67 (0.47)	0.67 (0.47)	0.75 (0.43)	0.74 (0.44)	0.74 (0.44)	0.73 (0.44)	0.73 (0.44)
Apartment	0.09 (0.28)	0.08 (0.28)	0.09 (0.29)	0.15 (0.35)	0.1 (0.3)	0.1 (0.3)	0.1 (0.3)	0.1 (0.31)	0.11 (0.31)

Notes: Mean and standard deviations (in brackets). Income in PPP Dollars was calculated using the OECD index (OECD, 2024). Solar panels, welfare, university, owned and apartment are binary variables. Therefore, mean values represent the proportion of dwellings with positive values for each variable. Monthly income, bedrooms and people are numeric variables.

Table 17 - Income (PPP Dollars) distributions for households

	Australia	Brazil
Quintile	2019-20	2022
Q1	2,363	581
Q2	3,821	960
Q3	5,661	1,519
Q4	8,278	2,555

Notes: These values are at the upper boundary for each quintile. The fifth quintile is not shown to avoid disclosing the maximum value for privacy reasons.

Table 18 - Summary of the variables used in the econometric models

Variable	Definition	Type	Reference (Australia)	Reference (Brazil)
sol_bin	Presence of a PV system in the household	Binary	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
qui_inc	Household income quintile	Categorical	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
survey_year	Survey year	Categorical	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
uni	University education of the household reference person	Binary	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
ln_inc_ihs	Inverse hyperbolic sine transformation of the household income	Numeric	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
pension	Welfare recipient household	Binary	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
tenure	Tenure Type	Categorical	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
dwel_struct	Dwelling Type	Categorical	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
nbedrooms	Number of bedrooms in the dwelling	Numeric	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
npersons	Number of persons in the dwelling	Numeric	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
qui_age	Age quintile of the household reference person	Categorical	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
state	State	Categorical	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)
area	Capital city or not	Binary	ABS (ABS, *[S.d.]*)	IBGE (IBGE, *[S.d.]*)

10 APPENDIX D

Second essay - Supplementary material: https://drive.google.com/file/d/1wFPGfo2Kb_jxxQfltJkTPIoUdAFU3n_c/view?usp=sharing

Third essay - Supplementary material: https://drive.google.com/file/d/1_2Kfkb-9c5-3TNNybvOxFOsUaqBw-KKc/view?usp=drive_link