Energy Research & Social Science 111 (2024) 103473

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Review

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

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ARTICLE INFO

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

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 article outlines future research agendas to expand upon the insights gained from this study.

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 [1]. 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 [2].

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 pre-defined 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 [2,3].

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 [4]. 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

Abbreviations: kW, Kilowatt; kWh, Kilowatt-hour; TW, Terawatt; PV, Solar Photovoltaic; DGPV, Distributed Generation Photovoltaic System; FiT, Feed-in Tariff; IEA, International Energy Agency; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analysis; WoS, Web of Science; USA, United States of America; OLS, Ordinary Least Squares; CGE, Computable General Equilibrium; SES, Socioeconomic Status; EEG, Erneuerbare-Energien-Gesetz policy; LMI, Low- or Moderate-income households; VAT, Value-added Tax.

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https://doi.org/10.1016/j.erss.2024.103473
Received 25 October 2023; Received in revised form 23 January 2024; Accepted 11 February 2024
Available online 23 February 2024

Sovacool and Dworkin [5] 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. [6], 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. [7], 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, policy-making, and public choices [8]. 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 [9].

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) [1] 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. [10], 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 [11].

In this context, this article seeks to evaluate, through a systematic review, the adoption of DGPV systems within the energy justice framework [5,6,8]. 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” [12]. 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 [13].

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. 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 [11]. In this paper, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework [14] is utilized as the foundation for the review.

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 [2].
3. Published in English language.
4. In peer-reviewed journals.

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.

1. Installations other than solar PV, such as solar thermal systems or other distributed generation sources such as biogas, wind, or hydro.
2. 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 [15].

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

1. Qualitative analyses, such as interviews with experts or opinion articles.
2. Focus exclusively on rural systems. In the literature, studies with an exclusive focus on rural areas are often associated with off-grid projects[1] and, therefore, were also excluded from the analysis.

[1] 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 [15]. This model has helped reduce poverty in rural areas of China [16].

3. Analysis for renewable sources in general, with no focus on distributed generation.
4. Based on the intention to adopt DGPV or forecasts, not on actual adoption data. Insights on intended uptake were provided by Schulte et al. [17].
5. Focus on solar cooking.
6. Impact assessments without distributional analysis.
7. Studies with no focus on economic inequality (e.g. racial disparities in rooftop PV adoption).
8. Studies on the economic feasibility of investment in DGPV.
9. Studies evaluating the technical potential of DGPV penetration, as the area available on roofs.
10. Other topics not related to the research.

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.

2.4. 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. Fig. 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.

2.5. Limitations

While this review provides a comprehensive analysis of the economic

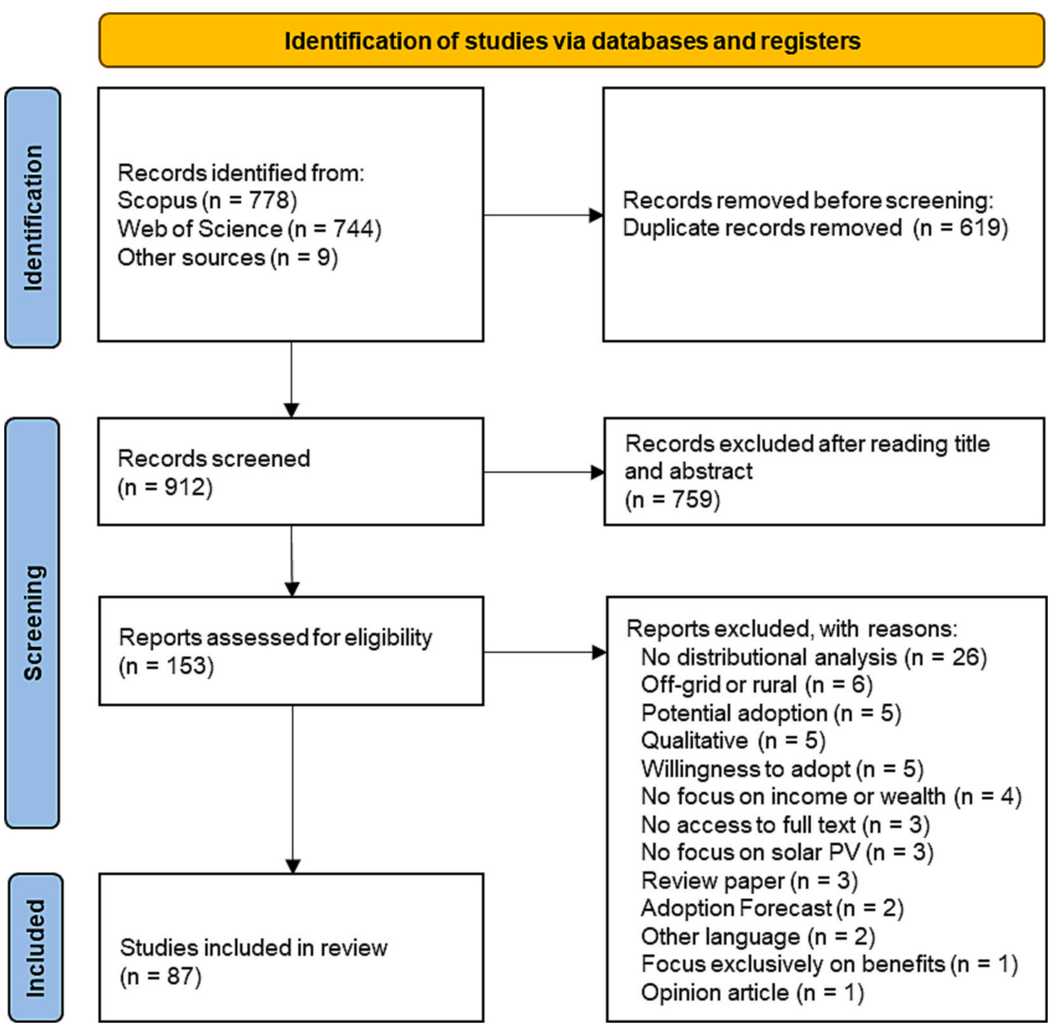

Fig. 1. Process of reviewed papers selection.

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.

1. 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.
2. 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 [18].
3. 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.
4. 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.
5. 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 [19]. Nevertheless, throughout this document, we address specific limitations of individual studies, offering a nuanced discussion that remains pertinent to the formulation of our conclusions.

3. Results and discussion

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 (Figs. 2 and 3).

In this context, it's worth noting that developing nations typically exhibit higher income inequality compared to advanced economies [20]. 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. [6], "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. The main characteristics of each study can be seen in Appendix A.

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

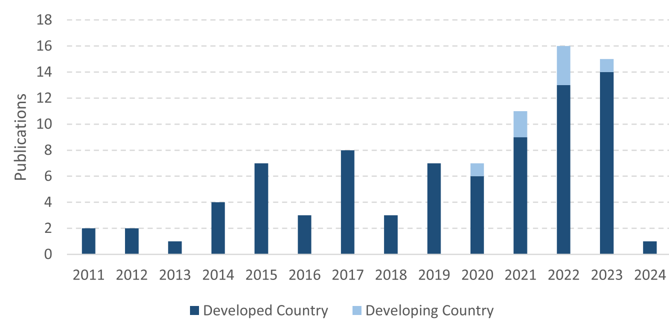

Fig. 3. Distribution by year of 87 publications under review. Data up to October 2023.

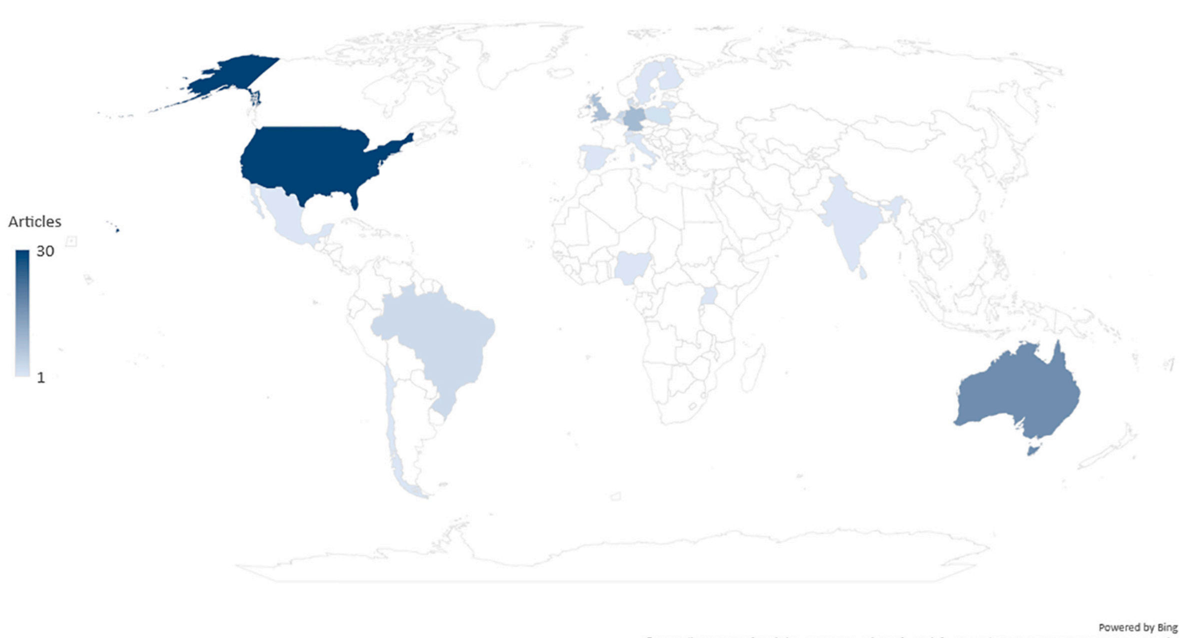

Fig. 2. Number of articles which cover each country.

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).

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 [21–28].

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 [29–33]. Another group used statistical tests (Kruskal-Wallis H, ANOVA, Randomization Test, Chi-squared) to verify differences in socioeconomic characteristics between adopters and non-adopters [24,34–36]. 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 [37–39]. 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 [38] or zero-inflated negative binomial regression models [40].

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 [32,41–45]. McConnell et al. [46], 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 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.

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. [47], 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.

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

3.2.1. Income and wealth inequality

In this section, 72 articles that evaluated the issue of inequality in the adoption of rooftop solar were analyzed (Table 3). We found that residential PV installations or subsidies for this technology are distributed unevenly according to income in 43 articles [21–23,25,28,29,32,34–38,40,4142,48–75]. 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 [30,31,33,76], building characteristics such as size and constructive quality [77,78], home value [79,80], financial inclusion index [81], and wealth [82–85].

In relation to wealth, it is worth mentioning that this metric is defended by some authors [68,69,84,85] 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

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

Relationship	References
Positive	Bao et al. [21], Thompson et al. [22], Varela-Margolles and Onsted [23], Etongo and Naidu [25], Vasseur and Kemp [28], Yu et al. [29], Costa and Santos [30], Fournier et al. [31], Grösche and Schröder [32], Lukanov and Krieger [33], Griffith et al. [34], Reames [35], Sigrin et al. [36], De Groote et al. [37], de Freitas [38], Kwan [40], Nelson et al. [42], Araújo et al. [48], Shittu and Weigelt [49], Schaffer and Brun [50], Darghouth et al. [51], Bennett et al. [52], Bernards et al. [53], Lekavičius et al. [54], Wicki et al. [55], Andor et al. [56], Poruschi and Ambrey [57], Grover and Daniels [58], Alderete Peralta et al. [59], Borenstein and Davis [60], Winter and Schlesewsky [61], Feger et al. [62], Dharshing [63], Hansen et al. [64], Stewart [65], Borenstein [66], Vaishnav et al. [67], Best et al. [68], Best et al. [69], Zhang et al. [70], O'Shaughnessy et al. [71], Kim et al. [72], Ros and Sai [73] Wang et al. [74], Poruschi and Ambrey [75], Macintosh and Wilkinson [76], Best [77], Jayaweera et al. [78], Best and Esplin [79], Kraaijvanger et al. [80], Aarakit et al. [81], Best et al. [82], Best [83], Best et al. [84], Best et al. [85], Tidemann et al. [86], Best and Chareunsy [87], Behnke and Shelton [88], Stewart [89]
No relationship	Keady et al. [24], Ruokamo et al. [26], Min et al. [39], Min and Lee [95], Lan et al. [96], Graziano and Gillingham [97], Balta-Ozkan et al. [98]
Negative	Simpson and Clifton [27], Stewart [89], Copiello and Grillenzoni [90], Olczak et al. [91] Palm [92], Zhang et al. [93], Irfan et al. [94]

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 [85]. 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 [69,83].

Two articles explored possible differences in the results according to the level of data disaggregation [86,87]. 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 [88], 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 [89] 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 [90] concluded that in Italy there was an inverse relationship between per capita income and installed PV capacity. However, the study was conducted at the municipal level, which may influence the result, as previously stated. Similar critiques can be applied to the studies conducted by Olczak et al. [91], Palm [92], Simpson and Clifton [27], and Zhang et al. [93], all of which identified a negative relationship, albeit at aggregate levels. Irfan et al. [94] 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, seven studies did not identify statistically significant results regarding the effect of income or other economic variables on the adoption of residential PV systems [24,26,39,95–98].

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 [99], lower rates of home ownership [51] and challenges in benefiting from subsidies in the form of tax credits [60] are among the additional reasons. From an electrical perspective, Hartvigsson et al. [100] 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 [101].

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. [36] 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 [64]. 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 [82–84]. In a study that covers a longer period (2012−2020), Best et al. [68] 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. [102] 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 [76] 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. [69] studied adoption patterns between 2012 and 2020 for renters, and found inequality has emerged and is widening over time. Finally, Stewart [65] 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. [71] 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 [66] 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 [33] 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. [67] 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 [38]. De Groote et al. [37] 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. [71], 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. [74] 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. [68] 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.

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. [42] 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 [41]. In contrast to the previous study, McConnell et al. [46] 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. [41] 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 [43,44,103]. 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 [104]. 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 [61]. Böhringer et al. [47] 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 [32]. According to Frondel et al. [45] 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 [105], 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 [106], but that do not explore their distributive effects between different income groups.

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

3.5. Recommendations to reduce DGPV adoption inequality and regressive impacts of incentive policies

3.5.1. Recommendations to reduce DGPV inequality

A series of studies recommended improving the targeting of subsidies to the poorest households [24,27,31,34,52,54,63,65,74,80,82,83,85,87,102,107]. 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 [68,69,77,79,82,83,85,87]. 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 [85]. Other authors [39,65,77,83] suggest that, in addition to wealth, the allocation of incentives to rented homes and

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

Inequality evolution	References
Inequality increase	Stewart [65], Best et al. [69], Macintosh and Wilkinson [76]
No difference	Sigrin et al. [36], Hansen et al. [64], Best et al. [68], Best et al. [82], Best [83], Best et al. [84], Chueca et al. [102]
Inequality decrease	Lukanov and Krieger [33], De Groote et al. [37], de Freitas [38], Borenstein [66], Vaishnav et al. [67], O'Shaughnessy et al. [71]

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

Economic impact	References
Regressive	Nelson et al. [41], Nelson et al. [42], Strielkowski et al. [43], Strielkowski et al. [44], Böhringer et al. [47], Andor et al. [56], Farrell [103], Cludius et al. [104], Többen [105]
Progressive	McConnell et al. [46]

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 [78,84], such as rebates. However, Best et al. [82] 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 [108]. 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 [34,51,54,84]. However, Darghouth et al. [51] 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 [60] 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 [33,51,54,67,68,89,97], 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. [51] 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 [107]. 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 [109] 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 [22,23,35,49,65,78,89,109]. Shittu et al. [49], 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 [23] argue that in addition to improving communication, incentive programs should have minimal red tape. Jayaweera et al. [78] 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. [71]. 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.

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 [58] 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. [45] 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. [47,110] 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. [44], 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 [103] 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 [111].

On the other hand, Feger et al. [62] 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. [44] 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 [103] in relation to the use of volumetric tariffs. In another study, Vaishnav et al. [67] 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. [112], 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. [8], 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.

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.

1. Greater geographic diversity: Only 9 % of the studies reviewed were concentrated on developing countries. Considering the higher inequality indexes in developing countries [20], 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 [2]. 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.
2. 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 [113]. Therefore, the racial theme could be further explored in future studies to provide more assertive information to policymakers.
3. 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.
4. 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.
5. 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 [107,109], 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.
6. 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.
7. 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.

5. Conclusions

This article 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.

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.

In terms of studies characteristics, it was possible to see that most of the studies examined the situation in developed countries, with only 9 % 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.

In summary, 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.

Funding sources

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. The funding source did not play a role in the study's design, data collection, analysis, interpretation, manuscript preparation, or the decision to submit the article for publication.

CRediT authorship contribution statement

Gabriel Konzen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Rohan Best:** Conceptualization, Resources, Supervision, Writing – review & editing. **Nivalde José de Castro:** Conceptualization, Project administration, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the authors used ChatGPT in order to enhance readability and rectify grammatical issues. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

Advice from the editors and reviewers is gratefully acknowledged. This advice contributed to substantial enhancements compared to the original version.

Appendix A

Table 6
List of papers reviewed.

Reference	Author	Year	Location	Level of analysis	Main methods	Income sign	Change in inequality over time	Type of impact
[76]	Macintosh and Wilkinson	2011	Australia	Postal Code	Distribution Charts	+	Increased	
[42]	Nelson et al.	2011	New South Wales (Australia)	Household	Distribution Charts, Electricity Market Model	+		Regressive
[41]	Nelson and Nelson	2012	Queensland (Australia)	General	Electricity Market Model			Regressive
[40]	Kwan	2012	US	Postal Code	Regression	+		
[46]	McConnell et al.	2013	Australia	General	Electricity Market Model			Progressive

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Table 6 (*continued*)

Reference	Author	Year	Location	Level of analysis	Main methods	Income sign	Change in inequality over time	Type of impact
[104]	Cludius et al.	2014	Germany	Not Applicable	Regression			Regressive
[32]	Grösche and Schröder	2014	Germany	Household	Correlation, Regression, Electricity Market Model, Inequality Metrics, Distribution Charts	+		Regressive
[23]	Varela-Margolles and Onsted	2014	Miami-Dade County - FL (US)	Census Tract	Survey/Interview, Distribution Charts	+		
[34]	Griffith et al.	2014	New Jersey and Massachusetts (US)	Postal Code	Cluster Analysis, Regression, Statistical Test	+		
[97]	Graziano and Gillingham	2015	Connecticut (US)	Census Tract	Regression	0		
[56]	Andor et al.	2015	Germany	Household	Regression	+		
[45]	Frondel et al.	2015	Germany	Household	Distribution Charts, Electricity Market Model			Regressive
[50]	Schaffer and Brun	2015	Germany	Region	Regression	+		
[28]	Vasseur and Kemp	2015	Netherlands	Household	Distribution Charts, Survey/Interview	+		
[36]	Sigrin et al.	2015	San Diego County - CA (US)	Household	Survey/Interview, Statistical Test	+	0	
[98]	Balta-Ozkan et al.	2015	United Kingdom	Region	Regression	0		
[57]	Poruschi and Ambrey	2016	Australia	Household	Regression	+		
[37]	De Groote et al.	2016	Flanders (Belgium)	Statistical Sectors	Regression	+	Decreased	
[60]	Borenstein and Davis	2016	US	Household	Distribution Charts, Inequality Metrics	+		
[66]	Borenstein	2017	California (US)	Household	Regression	+	Decreased	
[58]	Grover and Daniels	2017	England and Wales	Census Tract	Regression, Distribution Charts, Inequality Metrics	+		
[47]	Böhringer et al.	2017	Germany	Household	General Equilibrium Model, Simulation			Regressive
[63]	Dharshing	2017	Germany	County	Regression	+		
[105]	Többen	2017	Germany	Region	General Equilibrium Model			Regressive
[44]	Strielkowski et al.	2017	Northern England	Household	Electricity Market Model			Regressive
[67]	Vaishnav et al.	2017	US	Household	Cost-benefit Analysis	+	Decreased	
[27]	Simpson and Clifton	2017	Western Australia	Postal Code	Distribution Charts, Regression, Survey/Interview	–		
[78]	Jayaweera et al.	2018	Colombo District (Sri Lanka)	Census Tract	Regression	+		
[53]	Bernards et al.	2018	Netherlands	Postal Code	Regression	+		
[29]	Yu et al.	2018	US	Census Tract	Correlation	+		
[84]	Best et al.	2019	Australia	Household	Regression	0 for income and for wealth"	0	
[75]	Poruschi and Ambrey	2019	Australia's Capital Cities	Postal Code	Regression	+		
[33]	Lukanov and Krieger	2019	California	Census Tract	Regression, Correlation	+	Decreased	
[86]	Tidemann et al.	2019	Canberra (Australia)	Mesh Block	Distribution Charts, Regression	- for postcode and + for mesh block		
[61]	Winter and Schlesewsky	2019	Germany	Household	Inequality Metrics, Regression, Electricity Market Model	+		Regressive
[48]	Araújo et al.	2019	New York (US)	Postal Code	Regression, Cluster Analysis	+		
[43]	Strielkowski et al.	2019	Northern England	Regional	Electricity Market Model			Regressive
[30]	Costa and Dos Santos	2020	Brazil	State	Correlation	+		
[52]	Bennett et al.	2020	California (US)	Postal Code	Regression, Machine Learning	+		
[21]	Bao et al.	2020	California and Massachusetts (US)	Household	Survey/Interview, Distribution Charts	+		
[54]	Lekavicius, et al.	2020	Lithuania	Household	Simulation	+		
[31]	Fournier et al.	2020	Los Angeles County - CA (US)	Postal code	Correlation, Diffusion Model	+		
[35]	Reames	2020	Riverside and San Bernardino - CA, Washington - DC, Chicago - IL (US)	Census Tract	Regression, Statistical Test	+		
[92]	Palm	2020	Sweden	Municipality	Regression	–		
[82]	Best et al.	2021	Australia	Household	Regression	+		

(*continued on next page*)

Table 6 (*continued*)

Reference	Author	Year	Location	Level of analysis	Main methods	Income sign	Change in inequality over time	Type of impact
[85]	Best et al.	2021	Australia	Household	Regression	0 for income and + for wealth		
[96]	Lan et al.	2021	Australia	Postal Code	Machine Learning	0		
[94]	Irfan et al.	2021	India	Household	Regression	–		
[90]	Copiello and Grillenzoni	2021	Italy	Municipality	Time-series Analysis	–		
[91]	Olczak et al.	2021	Poland	Province	Regression	–		
[89]	Stewart	2021	Scotland	Data-zones	Regression, Distribution Charts, Piecewise Structural Equation Modelling	- for community solar and + for household		
[22]	Thompson et al.	2021	Southwest Nigeria	Household	Regression, Survey/ Interview, Distribution Charts	+		
[110]	Böhringer et al.	2021	Spain	Household	General Equilibrium Model, Simulation			
[103]	Farrell	2021	United Kingdom	Household	Simulation			Regressive
[24]	Keady et al.	2021	Vermont (US)	Household	Survey/Interview, Regression, Statistical Test	0		
[74]	Wang et al.	2022	46 states (US)	Census tract	Diffusion Model, Regression	+		
[83]	Best	2022	Australia	Household	Regression	+ (tenant)		
[87]	Best and Chareunsy	2022	Australia	Household/ Aggregate	Distribution Charts, Regression	- to aggregate and + to household level		
[62]	Feger et al.	2022	Bern (Switzerland)	Household	Structural Model, Regression	+		
[59]	Alderete Peralta et al.	2022	Birmingham (England)	Postal Code	Diffusion Model, Regression	+		
[38]	de Freitas	2022	Brazil	Census Tract	Regression	+	Decreased	
[107]	O'Shaughnessy	2022	California and Connecticut (US)	Postal Code	Regression			
[64]	Hansen et al.	2022	Denmark	Household	Regression	+	0	
[55]	Wicki et al.	2022	Poland	Region	Regression	+		
[65]	Stewart	2022	Scotland	Data-zones	Piecewise Structural Equation Modelling, Regression	+	Increased	
[25]	Etongo and Naidu	2022	Seychelles	Household	Regression	+		
[81]	Aarakit et al.	2022	Uganda	Household	Regression	+		
[77]	Best	2022	US	Household	Regression	+		
[51]	Darghouth et al.	2022	US	Census Tract	Regression, Distribution Charts	+		
[109]	Gao and Zhou	2022	US	Census Tract	Regression	Recommendation		
[49]	Shittu and Weigelt	2022	US	Utility Area	Regression	+		
[73]	Ros and Sai	2023	27 states (US)	State	Regression	+		
[69]	Best et al.	2023	Australia	Household	Distribution Charts, Regression	+	Increased	
[68]	Best et al.	2023	Australia	Household	Distribution Charts, Regression, LOWESS	+	0	
[93]	Zhang et al.	2023	Australia	Postal Code	Regression, Cluster Analysis	–		
[102]	Chueca et al.	2023	Brazil, Chile, Mexico	Household, Municipal, Regional	Regression		0	
[72]	Kim et al.	2023	Colorado (US)	Census Tract	Neural Network, Machine Learning	+		
[111]	Gunkel et al.	2023	Denmark	Household	Linear Optimization			
[26]	Ruokamo et al.	2023	Finland	Household	Regression, Survey/ Interview	0		
[70]	Zhang et al.	2023	Netherlands	Neighborhood	Regression	+		
[112]	Khan et al.	2023	New York (US)	Postal Code	Single Leader Single Follower (SLSF) game			
[95]	Min and Lee	2023	Seattle, Bellevue, Portland (US)	Census Tract	Statistical Test, Cluster Analysis, Regression	0 for socioeconomic and + for house characteristics		
[39]	Min et al.	2023	Seattle, US	Census Tract	Statistical Test, Cluster Analysis, Regression	0 for socioeconomic and + for house characteristics		
[80]	Kraaijvanger et al.	2023	The Hague (Netherlands)	Postal Code	Cluster Analysis	+		
[79]	Best and Esplin	2023	US	Household	Regression	+ for wealth (home value) and 0 for income		

(*continued on next page*)

Table 6 (*continued*)

Reference	Author	Year	Location	Level of analysis	Main methods	Income sign	Change in inequality over time	Type of impact
[71]	O'Shaughnessy et al.	2023	US	Household	Distribution Charts, Diffusion Model	+	Decreased	
[88]	Behnke and Shelton	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.

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