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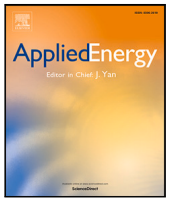

Review on fairness in local energy systems

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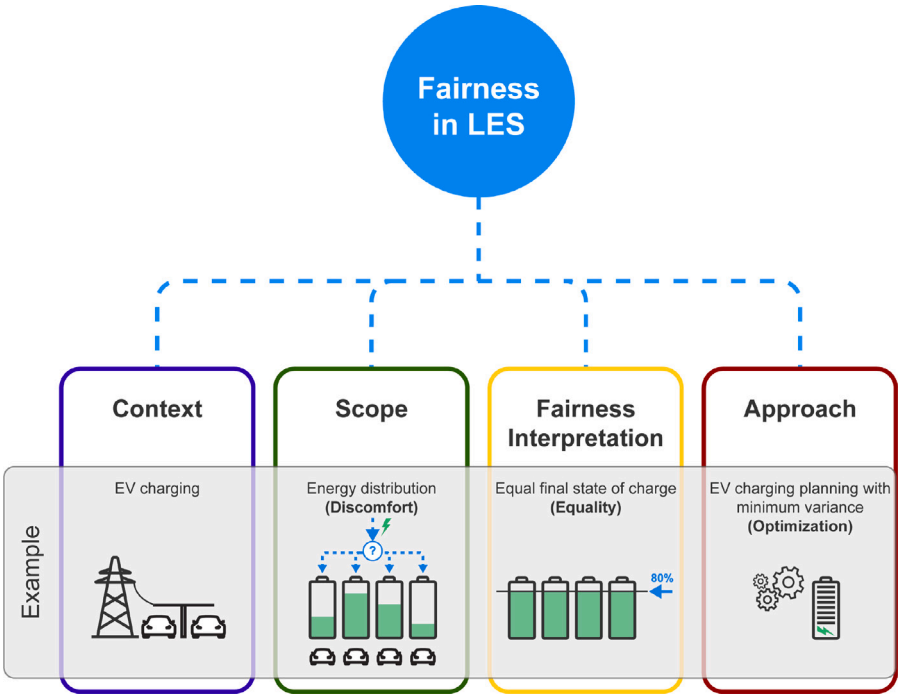
GRAPHICAL ABSTRACT



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ABSTRACT

The discussion of fairness is gaining considerable attention in the context of Local Energy Systems (LES). This is partially motivated by the energy transition, which has put more attention on technologies and production closer to the end-user. In other words, we are evolving towards a more user-centric approach, which requires dealing with fairness and justice due to the users' participation in the loop. Their willingness to participate depends on the perceived fairness regarding the systems they use. The current literature started to adopt the concept of fairness within LES but without a universally accepted approach. This review highlights the work described in the literature by thoroughly analyzing 80 scholarly papers addressing fairness in LES. The main

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objectives are twofold: to provide a definition of fairness within this domain and to examine how this concept is currently shaped and interpreted. The analyzed studies are categorized according to their applicability to LES, fairness and justice interpretation (e.g., equality, meritocracy), and use of post-method indicators to evaluate fairness performance. The work explores the identified gaps in the existing literature and outlines guidelines and prospective research directions for future studies addressing fairness issues in LES.

1. Introduction

The world is facing unprecedented challenges in dealing with the impacts of climate change caused by human activity [1]. The power sector is responsible for around 40% of the world's greenhouse gas (GHG)[1] emissions, and, therefore, many efforts have been made to reduce the footprint of energy generation in GHG emissions and mitigate the human impact on climate change. Recently, energy policies have adopted a user-centric approach, putting the consumer at the heart of the decision-making in the energy chain, namely through the increase of distributed production and technological advances, allowing energy trading on the user-level [2,3]. This new paradigm will contribute to the decarbonization goals envisaged in the Paris Agreement [4] but will raise new issues that must be addressed in current energy systems. Moreover, decentralized energy systems will contribute to the United Nations' sustainable development goals [5]. It is envisioned that this paradigm could be carried forward by focusing on Local Energy Systems (LES), including local electricity markets, energy communities, and energy management at the neighborhood and up to the city level [6]. To realize LES, automation in the form of algorithms, which act on behalf of a group of users, for example, on their energy trading, will play a key role since the user is not expected to be constantly willing to manually take care. Whenever an algorithm makes decisions that impact people and their communities, particularly on allocating collective assets, concerns about unfairness related to distribution, access, and responsibility arise.

The more consumers participate in energy trading with neighbors and grid services, the higher the importance of fairness. In addition, fairness is a decisive factor influencing the user acceptance of smart grid technologies according to a previous survey [7]. Hence, it is necessary to consider responsible algorithms and fairness aspects in LES. Recent literature has started to address fairness-related issues in the development of algorithms, with many articles having been released recently on this topic [8–11]. Different algorithm designs may lead to variations in benefits and risks [9]. Improving algorithm governance would enable accountability and responsiveness in designing and using those algorithms to prevent discrimination of participants of LES, negative effects on the consumers, or social unrest to the public [9].

The present article focuses on fairness in LES; however, it is essential to clarify what is the meaning of a "local" energy system since that definition delimits the scope of action of the analyzed literature. An LES in the literature ranges from single-building systems to anything below the high-voltage transmission level. Beyond that definition, a "smart" LES can be seen as an extension of smart grids, characterized by a decentralized energy generation (which end-users can provide), typically sourced from renewable or low-carbon sources [12]. For clarity, and following the discussion raised by Devine-Wright [13], the adopted definition of LES is a decentralized approach to energy generation, management, and consumption at the community or regional level. Initially, the LES concept aimed to empower communities to initiate energy projects regardless of their background or location. However, the focus has shifted to collaboration with local authorities and enterprise partnerships, emphasizing 'smart' systems integrating digitalization and various energy aspects [13,14]. This evolution includes government-funded demonstrator projects and the development of new technologies and services, strongly emphasizing national economic growth and energy system transformation alongside addressing local energy challenges.

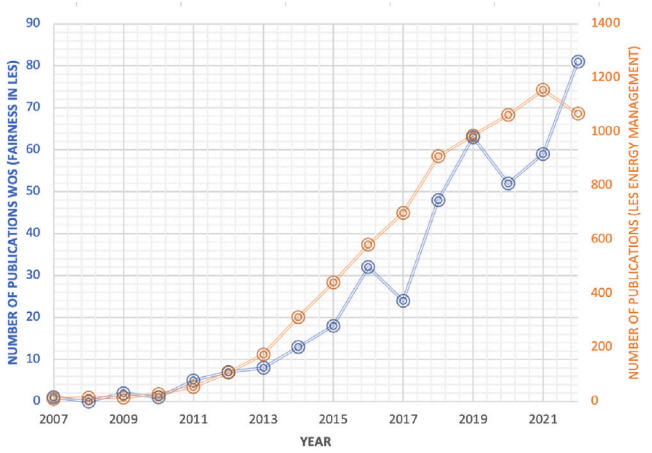

Fig. 1. Number of publications per year. Around 400 publications have been retrieved from the WoS database dating between 2007 and 2022, with the term "fairness" being searched in papers related to the context of LES (blue) vs. around 7600 publications related to energy management in LES (orange). The year 2008 did not return any publication related to fairness in LES.

A literature search on the Web of Science (WoS) has returned around 400 publications dating between 2007 and 2022, with the term "fairness" being present in papers related to the LES context (blue) vs. around 7600 publications related to energy management in LES (orange) (cf. Fig. 1). Specifically, the adopted definition of LES includes works that deal with local energy communities (LEC) [15], demand response (DR), microgrids, distribution networks, and electric vehicle (EV) charging management [16]. Around 85% of the literature has been produced recently, between 2016 and 2022. The growing trend is especially noticeable for the works dealing with fairness in LES, averaging around 50 publications annually since 2016, with an average annual growth rate of 31%. This compares to 920 publications per year (14% average annual growth) in the same period of 2016–2022 for the more general topic of energy management in LES.

It has been noticed that analyzing how fairness is addressed in current studies is a difficult task. The hindrance is that the interpretation of fairness is not uniform across the existing body of scientific literature [10,17,18]. In fact, classical concepts of justice and fairness from philosophy, sociology, or psychology also entail different views. Additionally, other than being common in social science, a systematic discussion of different perspectives that leads to more conceptual precision is still lacking, so standards for fairness in energy systems must still be developed. Yet, in the different contexts of LES, fairness is important, for example, when cost or money is distributed across an energy community or when addressing the comfort of different participants. Moreover, the perception of fairness, as seen by energy consumers in the LES context, is increasingly being discussed in several venues and research works [7]. For example, users might be concerned about how the so-called intelligent applications calculate and distribute the benefits among neighbors. Participants might feel upset if they believe others are being luckier or there are biased outcomes. Therefore, a systematic review of fairness in LES is required to provide a clearer

[1] IEA. The role of CCUS in low-carbon power systems (2020). URL https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems.

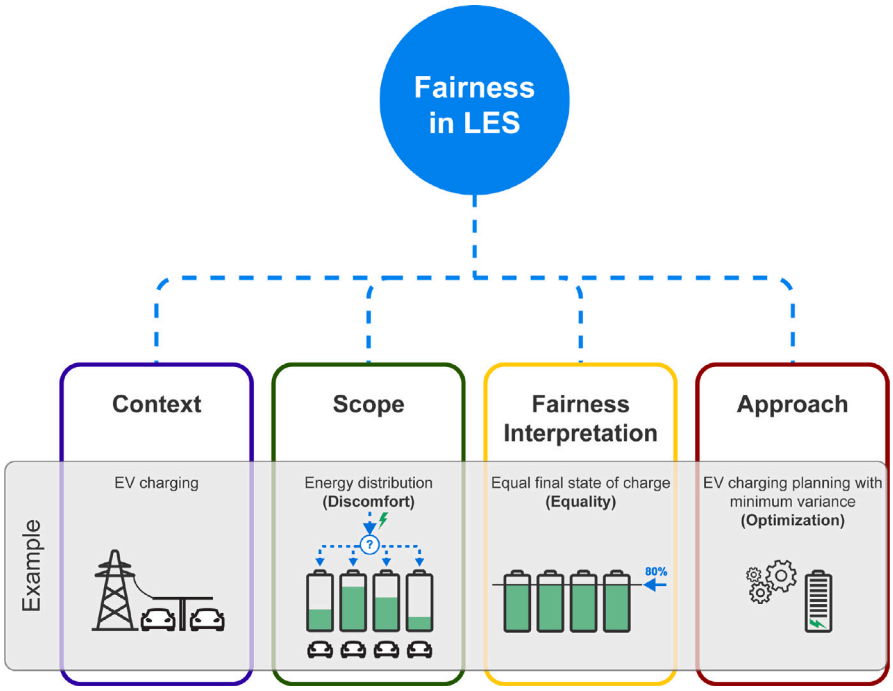

Fig. 2. Articles are classified in this review by their context and scope (refer to Section 3), fairness interpretation (refer to Section 4), and the adopted approaches to achieving fairness (refer to Section 5). In the figure, an example is given for the case of EV charging.

orientation for those involved in the field to develop better and fairer applications for LES. A recent work classified 20 papers related to different energy-sharing methods in energy communities [18] in terms of fairness interpretation and indicators. The article has limited state-of-the-art coverage and only focuses on energy communities, while the present review paper addresses the broader scope of LES as earlier defined in this section, namely analyzing 80 scholarly articles classified in the defined domain and related to fairness. Currently, to the best of the authors' knowledge, no article attempts to provide a systematic classification and interpretation of fairness of existing related literature in the LES domain. Hence, this review's contribution is to systematically provide an analysis of recent works dealing with fairness aspects in LES. Indeed, an attempt is made to define what is fair and how fairness is understood in this field. Research studies are classified according to their applicability in LES, the fairness aspects, and the several post-method indicators that can evaluate fairness performance. To the best of the authors' knowledge, this is the first review paper that attempts to summarize the current body of literature dealing with fairness aspects in LES. This work further contributes to discussing the current gaps in the literature and provides guidelines and research avenues that could be the foundations of future research to tackle fairness issues in LES in the coming years.

Fig. 2 presents an example of the classification of the articles by their Context and Scope.

As outlined in Fig. 2, the present work provides an analysis and classification of the reviewed articles with respect to the following four aspects: (a) the context in which fairness is addressed (refer to Section 3); (b) the scope, i.e., what should be made fair (refer to Section 3); (c) the fairness interpretation, i.e., how fairness is defined (refer to Section 4); and (d) the approach to achieve fairness (refer to Section 5). The figure illustrates these aspects in the example of fair distribution of a limited amount of energy to multiple electric vehicles (EVs). In this example, the context is EV charging and the scope is the distribution of energy, which affects the (dis-)comfort of the users. An energy distribution might be interpreted as fair if the EVs depart with similar states of charge (SOCs), which could be achieved by considering the variance in the SOCs in the objective function of the charging planning algorithm.

2. Methodology of review

The presented systematic review of fairness in LES has been made considering the PRISMA methodology [19]. The databases used to search for articles have been Web of Science, Science Direct, IEEE Xplore, and ACM. The search terms for the initial analysis conducted on the databases have considered the combination of the terms "Fairness" and "Fair" with the terms "Local Energy Systems", "Local Energy Market(s)", "Energy Community(ies)", "Demand response", "Microgrid", "Peer-to-Peer Energy", "Smart Building(s)", "Energy Sharing", and "Local Flexibility".[2] The literature search results are summarized in Fig. 3.

In the first step, entries have been identified based on the search terms, resulting in Dataset I with 1261 items. In the second step, 307 entries have been eliminated, considering duplicated, non-related, and non-English items, resulting in Dataset II with 954 entries. In the third step, another 641 items have been removed by analyzing the title adequacy, resulting in Dataset III with 313 entries. The title adequacy lets the authors exclude works unrelated to "energy applications" (e.g., telecommunications, peer-to-peer information exchange) or studies with scope outside the distribution/local level of the value chain. In the fourth step, 253 records have been eliminated considering abstract adequacy, resulting in Dataset IV, with 60 entries. Finally, an ad-hoc search on Google Scholar have been performed not to miss relevant works that might not be identified in the initial search. From this ad-hoc search, 20 additional works have been included in Dataset IV, resulting in the final Dataset V with 80 entries.

3. Context and scope

LES are evolving fast, driven by changes in technology, regulatory frameworks, and societal needs. This evolution has led to diverse applications and contexts within LES, each with unique characteristics and

[2] Search string: (Fair ∪ Fairness) ∩ (Local Energy Systems ∪ Local Energy Market(s) ∪ Energy Community(ies) ∪ Demand response ∪ Microgrid ∪ Peer-to-Peer Energy ∪ Smart Building(s) ∪ Energy Sharing ∪ Local Flexibility).

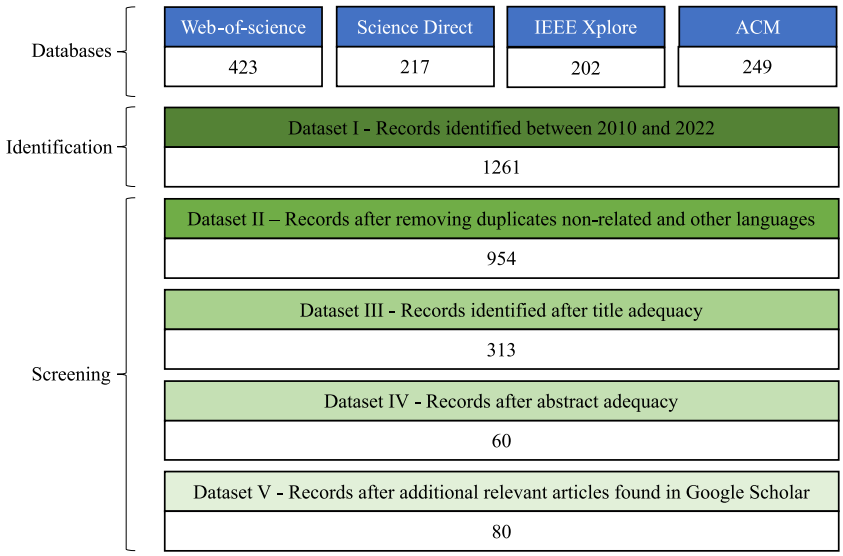

Fig. 3. Number of database entries considering each step. 1261 works between 2010 and 2022 have been collected using the defined keywords from four databases. After finalizing the screening process, the number of works has been reduced to 80.

Table 1
Contexts in Local Energy Systems (LES).

Context	Definition	Key characteristics
LECs	Community-based initiatives to collectively manage and share energy resources.	Decentralized energy management, energy autonomy, community engagement, local energy markets.
DR	Dynamic response to grid signals and market conditions to enhance grid reliability, efficiency, and cost-effectiveness.	Grid load management, peak shaving, demand-side management, and dynamic pricing.
(LEC) Microgrid	Physical microgrid (or part of a distribution network) connecting end-users within the broader framework of LECs.	Grid resilience, flexibility, self-sufficiency, market strategies in the context of microgrids.
Distribution Networks	Energy distribution infrastructure evolving with emerging technology.	Cost-effective energy distribution, grid operation, grid reliability, distribution infrastructure.
EV charging	Integration of transportation and energy systems for efficient and sustainable mobility.	EV infrastructure, charging station operation, integration with RES, market incentives.

challenges. Recognizing this complexity, the present analysis aims to provide a nuanced understanding of fairness within LES by delineating key contexts and scopes. Acknowledging the broad scope of LES, which encompasses a wide range of energy systems, from single-building to community-scale initiatives, is crucial. This decentralized energy generation, management, and consumption approach reflects a shift towards collaborative frameworks involving local authorities, enterprises, and community stakeholders. This section examines fairness in LES by exploring key contexts and scopes.

To effectively analyze fairness within this evolving landscape, five key contexts representing focal points for addressing challenges and opportunities in LES have been identified: Local Energy Communities (LECs), Demand Response (DR), (LEC) Microgrids, Distribution Networks, and EV Charging Mechanisms. Each context captures a distinct aspect of LES, ranging from community-based energy initiatives to integrating transportation and energy systems for sustainable mobility. Table 1 summarizes the key contexts in LES, their definitions, and their characteristics, offering a clear reference point for understanding the proposed analysis.

Subsequently, this work categorizes stakeholder perceptions of fairness, emphasizing factors like profit distribution, cost allocation, energy-sharing mechanisms, trading engagement, user experience, and satisfaction, among others. These perceptions are grouped into three overarching scopes: benefit distribution, (dis)comfort, and pricing. Table 2 summarizes these scopes with practical examples, ensuring a comprehensive exploration of fairness in LES. The criteria for grouping such factors into these three scopes are based on their relevance to fairness within LES. Benefit distribution encompasses economic profit allocation, while pricing focuses on cost mechanisms. (Dis)comfort emphasizes user experience and satisfaction. These scopes are interconnected, with factors related to comfort influencing profit distribution and pricing and vice versa. The holistic analysis of fairness within LES requires considering all scopes, although some literature mainly focuses on specific aspects.

3.1. Context analysis

Fig. 4 presents the context and the scope of the reviewed publications related to fairness in LES.

The first context, "Local Energy Communities (LECs)" (top bar in Fig. 4), is the most extensive one, since it relates to different aspects of fairness. LECs are community-based initiatives that enable residents and service providers to collectively manage and share energy resources (e.g., renewables and storage systems). The context of LEC considers works dealing with fair mechanisms of energy sharing [20,26–29], fair pricing and cost allocation schemes [10,15,30,31], and the transparent and democratic decision process of investments [32] and resource management [33,34] within the community.

The second context, "Demand Response (DR)" (second bar from top to bottom in Fig. 4), focuses on the optimization of customers' load profiles (in the form of DR programs) incorporating related aspects such as consumption patterns of appliances [35–37], pricing and cost allocation mechanisms [38–40], end-user satisfaction levels [41,42], among others. The literature analysis shows that the context of "demand

Table 2
Scopes in LES.

Scope	Definition	Key work[a]	Examples
Benefit distribution	Allocation of economic profits, encompassing both costs and revenues, within the LES framework.	[20,21]	- Fair billing mechanisms. - Profits in peer-to-peer energy markets. - Cost distribution in community renewable energy usage. - Profit sharing in incentive-based power curtailment.
(Dis)comfort	User experience and satisfaction with LES energy services.	[22,23]	- Demand-side management for user comfort. - User-friendly energy sharing. - Services meeting environmental goals with minimal discomfort.
Pricing	Mechanisms for determining, setting, and allocating costs in the LES.	[24,25]	- Transparent tariff structures. - Pricing models encouraging energy-efficient behavior. - Adjusting costs based on user demand and consumption patterns.

[a] The selection of key works has been done considering the approach of Appendix C.

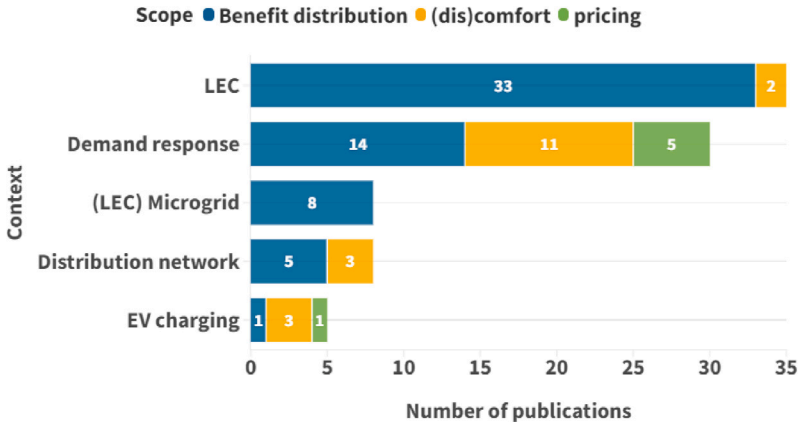

Fig. 4. Number of publications in each context and scope. It can be noticed that the literature is dominated by the LEC context and the benefit distribution scope.

response" is tightly related to fairness, probably due to the potential benefits of modifying the peak load and the residential demand profiles and end-user participation incentivized by fair DR programs.

The third context, "(LEC) microgrid" (third bar from top to bottom in Fig. 4) focuses specifically on microgrids. While LECs and microgrids share some characteristics, such as the generation and distribution of energy in a localized area, the two contexts have been distinguished by considering a microgrid as a physical distribution network (or part of one distribution network) connecting all the end users. In contrast, LECs are not necessarily physically constrained to a certain area, and participation is voluntary [34]. The context of "(LEC) microgrid" considers works dealing with cooperative [43,44] and non-cooperative [45] trading and market strategies in the context of microgrids. It also includes studies addressing the fair allocation of costs among multi-carrier energy systems or the modeling of users' behavior and dissatisfaction considering power system constraints [46].

The fourth context, "distribution network" (fourth bar from top to bottom in Fig. 4), focuses on the impact of certain activities and interactions of players on the grid. Topics of interest in the "distribution network" context include voltage control strategies to mitigate fast voltage violations [47–49], mechanisms for cost-sharing mechanisms related to the use of common infrastructure and services in the grid [50,51], and power system reliability (including the reliability level for individual end-users) [52].

Finally, the fifth context includes works in which "EV charging" schemes are the focus of the study (bottom bar in Fig. 4). The demand for EVs has been steadily increasing over the past few years. Therefore, the availability and accessibility of EV charging infrastructure is expected to affect the fairness of the electricity system. Works in the context of "EV charging" deal with aspects of fair charging management [53,54] and pricing schemes [55]. Ensuring fairness in this context requires ensuring that EV charging infrastructure is accessible to all users, regardless of location or income level, and that the charging process does not unfairly impact the electricity system or certain groups of users.

3.2. Scopes literature analysis

The various contexts in LES involve interactions among different actors. Defining what constitutes a "fair" LES is challenging, as each participant seeks fairness from their own perspective. Literature analysis indicates that actors prefer participating in LES perceived as "fair" regarding profit distribution, cost allocation, energy-sharing mechanisms, and engagement in trading activities. These fairness perceptions have been condensed into three scopes: benefit distribution, (dis)comfort, and pricing. Fig. 5 illustrates these scopes, showing how diverse actor perspectives contribute to a "fair" LES.

As shown in Table 2, this review has identified two key works for each scope. Key works refer to articles that significantly contribute to understanding specific topics within the scopes of benefit distribution, (dis)comfort, and pricing in LES.

For instance, for the benefit distribution scope, the key works [20,21] provide an analysis of benefit distribution in peer-to-peer energy markets. The authors in [20] offer a detailed analysis of peer-to-peer mechanisms and serve as a foundational source for understanding how these mechanisms impact the equitable distribution of benefits among participants. Additionally, [21] provides important insights into fair energy trading practices, highlighting how such practices can contribute to a more equitable benefit distribution in LES. The benefit distribution scope also includes papers searching for a fair billing mechanism (sometimes referred to as cost allocation) to remunerate DR participation [38,39,56–61], fair peer-to-peer market mechanisms

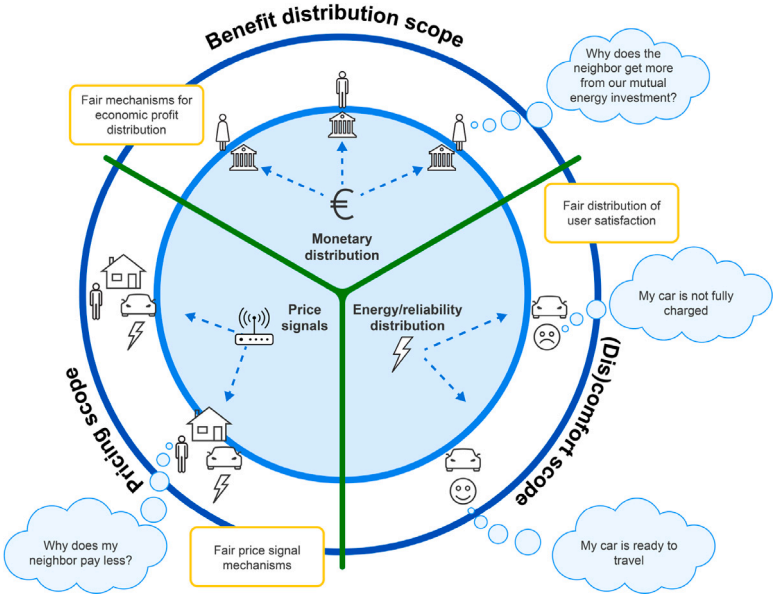

Fig. 5. An example of the three overarching scopes in action. Notice that different actors' perspectives contribute to a "fair" LES.

and profit distribution (sometimes referred to as profit allocation) [29,43,44,62–67], or other special cases of benefit distribution such as community usage of renewable energy in EV charging schemes [54], community energy storage system usage [68], or incentive-based power curtailment strategies [47,49]. Overall, the "benefit distribution" scope relates to how monetary or economic profits are handled within the LES.

The "(dis)comfort" scope relates more to the user experience and satisfaction. This scope considers how well the energy services provided by the LES meet the needs and expectations of end-users. It is not solely about the financial aspects but also about ensuring that users are comfortable with how the system operates. The "(dis)comfort" scope is closely related to DR and how the demand side management actions are implemented and performed considering the participation of end-users [36,41,42,69–73]. It also includes other cases of "(dis)comfort", such as those related to energy sharing mechanisms and how those mechanisms impact the needs of users [22,35,51,74]. In particular, the key works [22,23] analyze energy sharing and peer-to-peer frameworks and their impact on user comfort (linked to the (dis)comfort scope as shown in Table 2). Key work [22] examines energy sharing for smart buildings with local battery systems and aggregated electric vehicles, providing insights into how such systems affect participant comfort and convenience. Additionally, the key work [23] presents automated peer-to-peer negotiation for energy contract settlements in residential cooperatives, highlighting how these automated processes can reduce discomfort and distribute energy sharing among participants.

Finally, the "pricing" scope includes how users adapt their behavior based on cost structures, the fairness of tariff systems, and the financial incentives or disincentives that encourage or discourage certain energy consumption patterns. While "pricing" may be related to benefit distribution and user comfort to some extent, it should be noted that its main emphasis lies in the pricing mechanisms. Therefore, the "pricing" scope does not subsume the "(dis)comfort" or "benefit distribution" scopes but rather arises from complementing those in exploring different aspects of fairness within LES [24,25,40,55,61,75]. The key works [24,25] study pricing strategies in peer-to-peer energy markets. Authors in [24] examine personalized real-time pricing for efficient and fair DR in energy cooperatives and highly competitive flexibility markets, offering important insights into how such pricing strategies can promote fairness. Additionally, the key work [25] explores the incorporation of fairness within DR programs in the smart grid, showing how fair pricing mechanisms can ensure equitable participation and benefit distribution among participants.

From Table A.8 and Fig. 4, it is evident that most of the works focus on the scope of benefit distribution (61 articles from the database). This is not surprising given the nature and relation of fairness to monetary aspects (although not exclusively) from the different stakeholders. Also, the intersection of the "LEC" context and "benefit distribution" scope is extensively studied in the reviewed literature, showing the impact that studying fairness has in enabling active participation from end-users while meeting the goals of network operators and utilities. However, there is a limited exploration of the connections between the "(dis)comfort" and "pricing" scopes. Furthermore, unexplored areas remain at the intersections, for instance, of the "pricing" scope with the "LEC", "(LEC) Microgrid", or "distribution network" contexts. These gaps in research merit further investigation, as they have the potential to advance understanding of fairness in LES and contribute to societal goals such as equitable access to energy and sustainable development. Additionally, addressing these gaps could have broader implications for policy-making, stakeholder engagement, and the resilience and sustainability of LES.

4. Classifying and interpreting fairness

In this section, the reviewed works are classified in terms of philosophical views on fairness. The idea of fairness, closely intertwined with notions of justice, holds a pivotal position within the realms of moral, legal, and political philosophy [76]. Fairness interpretation in the energy domain often find their origins in these classical theories.

4.1. Classical principles of fairness

One central view on justice, dating back over two millennia, refers to the fair allocation of material and abstract goods, like public funds, positions, or honors, as well as burdens (e.g., military service) among free citizens. Aristotle proposed an approach where goods should be distributed between people proportionately to what each person deserves [77]. After him, the question of what is deserved when getting prestigious positions, good jobs, or material goods has caused many discussions. Equality is typically seen as the default principle. However, if there are relevant features, it is acceptable to deviate from that.

For instance, if a person has put in more effort to make the social community flourish, they might deserve a more significant share of what is achieved together [78]. If effort and contribution are the main factors for distribution, these are assigned to the meritocracy theories of fairness.

Theorists in the humanistic tradition have challenged meritocracy approaches [79] where it is argued that a priority of absolute standards, meaning certain goods, for instance, basic health care should be allocated independently from individual merits and contribution. John Rawls' famous Theory of Justice also stands against meritocracy. Rawls argues that it is legitimate that individual efforts result in higher gains but only if these gains also go hand in hand with considerable advantages of least advantaged members of society [80]. Rawls declares this claim as the difference principle, later also referred to as the min–max principle. Arguments for one or the other approach are closely linked to the context and distributive good under negotiation.

In general, attributes like race, gender, social origin, and religion are considered unreasonable or inappropriate to deviate from an equal distribution pattern. This outcome can be directly or indirectly traced back to such features that declare the distribution as unfair discrimination [81]. Developing strategies to mitigate unfair discrimination is a significant topic in the algorithmic fairness community, e.g., for algorithmic pretrial risk assessment [82].

The principles introduced above are mostly considered under the complex of distributive fairness, which refers to distributing benefits and obligations fairly and justly among people. There are other fairness perspectives, including [18]: intergenerational fairness, procedural fairness, and restorative fairness. For instance, a procedural fairness perspective is strongly related to mechanisms of transparency, possibilities for intervention, and the feeling of respect.

4.2. Classification based on classical principles

The scope of distribution of costs and benefits accounts for more than 70% of the reviewed articles regarding fairness in LES (cf. Fig. 4 in Section 3 - Context and Scope), so classical principles for distributive fairness must be considered when categorizing the reviewed literature. The reviewed works often lack explicit connections to their classical fairness origins. The authors have extensively reviewed the works to identify and propose the most suitable classifications. In this work, three distributive fairness principles have been identified, namely:

- Equality: The primary objective for distribution is to ensure that participants receive an as equal as possible share of the respective goods or burdens.
- Min–max fairness: The primary objective for distribution is to ensure an allocation of resources that maximizes the minimum benefit received by any user. The fairness objective is adopted from Rawls' difference principle.
- Meritocracy: The primary objective for distribution is to ensure that the distribution of respective goods and burdens is subject to participants' merits and contributions. Participants who are more invested in the cooperative practice, either in terms of finance, materials, or their social contribution, are rewarded in the distribution.

For nearly all the approaches, it can be said that they aim to ensure, with their dedicated focus, that every participant of a reference area, e.g., people or users who are engaged together in a local energy community, receive a fair share of the respective goods. This can be material goods, like financial profits, or subjective goods, such as user satisfaction. However, this review has not focused on identifying any work that considers other fairness perspectives, such as procedural fairness or those addressing unfair discrimination.

In the reviewed literature, the equality fair criterion is achieved by minimizing the differences between the ratio of the profit or benefit compared to the maximum profit that would be theoretically possible within the group of users [64]. It is also possible to find approaches where user (dis-)satisfaction as subjective perception is considered the distributive good to be minimized or maximized between participants (cf. Table 3, half of the articles reviewed in this survey have been classified in the equality category).

Table 3
Classification of the reviewed articles in terms of defined interpretations of fairness: Three classifications of interpretation of fairness are adopted. The table shows the works that fit the definition and the total number out of 80 reviewed articles.

Interpretation of fairness	Total	References
Equality	44	[10,11,20,21,23,25,26,28,30,31, 33,35,37,41,42,47–55,62,64,65, 69–75,88–97]
Min–max fairness	5	[36,41,73,74,83]
Meritocracy	43	[10,15,16,22,24,25,27,29– 32,34,38–40,43–47,50,53,56–61, 63,64,66,68,84–87,93,98–102]

Min–max fairness has been extensively applied in the context of communication networks and is being increasingly adapted to the LES context. In fact, it has been possible to identify a few studies [36, 41,73,74,83], especially from the DR context [36,41,73]. Min–max fairness criterion is adapted for different purposes in LES, e.g., the fair allocation of power to air conditioners [36] (DR context), where the system is min–max fair if the temperature setting in any house cannot be decreased without increasing temperature in another house with a higher setting.

More than half of the reviewed works in this survey have been classified as defining fairness using meritocratic principles. For example, the idea behind one framework [84] is to assign losses to each transaction based on its contribution to the real and reactive flow of each line on its path. Therefore, those with merit to contribute better to the power grid efficiency will benefit more. Another study within the LEC context also proposes that the system rewards those with allocation of more surplus PV energy if they are willing to pay more, i.e., they have the desire to pay for green energy [34]. Many works that use the Shapley Value[3] fall into the meritocratic fairness principle, in which the rewarding mechanism is based on the contribution of the users [27,29,44,59,85–87].

Table 3 shows the proposed classification of the reviewed body of literature regarding the different principles of fairness interpretation as described above.

Similarly, Fig. 6 shows the chronological classification of reviewed works regarding the interpretation of fairness. Here, the bars represent the number of works fitting each category and by year: blue for meritocracy, yellow for equality, and green for min–max fairness.

It is important to highlight that some articles that have been reviewed mention the problem of coalition stability [15,32,43,62,63]; Coalition stability means that none of the system's users has an incentive to leave the group, also known as internal stability, while external members have no advantage in joining, known as external stability [103]. Most studies deal with internal stability issues in LES [15, 27,32,43,62]. The scalability of coalition models to larger instances is an ongoing challenge [15,32]. The 5 articles related to coalition stability have been classified as meritocracy since the proposed algorithms weigh the contributions of each member. Another work provides methods that can combine meritocracy, equality, and stability [32].

5. Approaches for achieving fairness

This section thoroughly organizes decision-making strategies, economic and game-theory concepts, and indexes found in the literature

[3] Please refer to Section 5.2 for more details on Shapley Value concept.

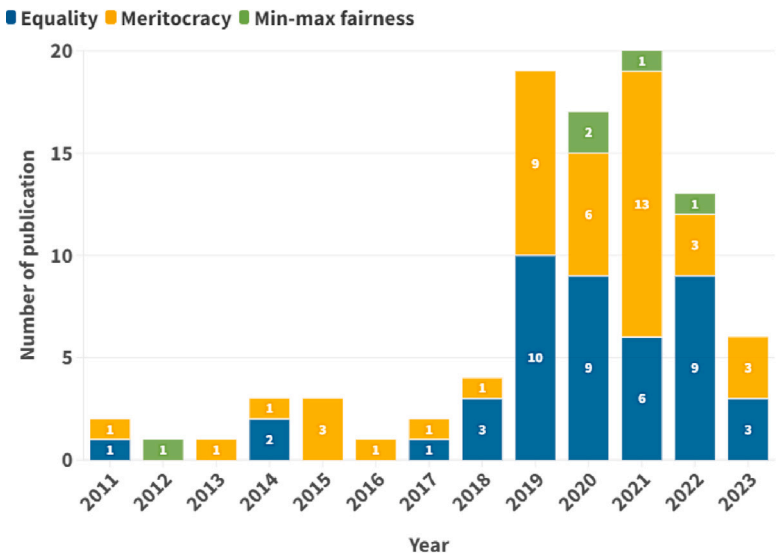

Fig. 6. Classification of reviewed publications in terms of fairness interpretation: 80 publications have been classified considering the publication year and the fairness interpretation.

claiming fair LES. Section 5.1 categorizes "decision-making strategies" in fairness approaches, Section 5.2 made a classification of "economic and game theory concepts" and Section 5.3 exposes the most used indexes.

5.1. Decision-making strategies used to achieve fairness

Decision-making strategies offer ways to approach complex problems using different mechanisms. The authors of the analyzed articles carefully designed these strategies to align with the specific fairness goals of the LES system or context in which they are applied. The authors of this work classify decision-making strategies into rule-based and optimization.

Rule-based methods define rules derived from the insights obtained while modeling fair systems. Applying these rules guarantees the system's fairness and gives insight into how a model would function under various scenarios. For instance, according to Ref. [95], a selection of consumers to curtail energy is performed by executing a set of rules. Under these criteria, consumers are selected proportionally to their participation and the amount of energy curtailed in the past. Rule-based strategies are split into two sub-categories:

- Distribution: includes methods in which the resources or benefits are distributed according to some criteria, such as merit or social welfare. For instance, a distribution mechanism is implemented considering a rule-based method (pricing scheme) to distribute the energy in storage systems by merit in Ref. [75]. The pricing scheme is used to find a good trade-off between the interests of a service provider and the end users.
- Redistribution: these methods consider an ex-post distribution of resources or benefits executed after an initial distribution process. This initial process can be an optimization mechanism where a solution is obtained without fairness consideration, and subsequently, a redistribution is executed considering fairness aspects. For instance, in Ref. [100], the benefits are redistributed considering an initial set point obtained using a demand-side management approach. Fairness is ensured under this scheme following redistribution rules based on the contribution of each member to the overall system.

On the other hand, optimization strategies are mechanisms to find the best distribution of resources or benefits among a set of possible options. These strategies implicitly provide the best fair option depending on the interpretation of fairness. The works under this category usually involve defining an objective function and finding the input variables that maximize or minimize such a function. For instance, the authors in [26] present an optimization for determining a peer-to-peer fair energy-sharing scheme where the distribution of resources is determined based on a cost reduction ratio distribution. Optimization strategies can be classified depending on how fairness is implicitly considered in the model as:

- Objective function: fairness is included in the formulation of the objective function, i.e., the solutions obtained are fair under the criterion that is optimized in the objective function. For instance, in Ref. [31], the authors propose a method of electricity cost-sharing in energy communities via an optimization where the objective function considers dynamic cost parameters to ensure fairness in the cost distribution.
- Constraint: fairness is obtained considering a range of expected values on a given criterion that the users are likely to accept as fair, and the perceived fairness is constrained between a maximum and minimum bound. For instance, in Ref. [69], the authors select the customers to participate in demand response programs, using their response delays as the metric reflecting reliable customers, i.e., the constraints are designed to favor customers with better response time to the events.

Table 4 presents the distribution of analyzed works into different decision-making strategies.

5.2. Economic and game theory concepts used in LES

The literature addressing fairness in LES uses some "economic and game theory concepts" offering different methods or principles to achieve fairness in various LES contexts. Table 5 presents the identified concepts often employed in the approaches studied in this review.

The Shapley Value (SV) [104] is a concept from cooperative game theory that assigns a value to each player in a cooperative game based on their marginal contribution to different coalitions as a way to fairly distribute the worth of a joint endeavor among the participants. The SV ensures that each player is rewarded based on their marginal contributions to the grand coalition (the full group of players) and all possible smaller coalitions. It achieves fairness by averaging over all possible combinations in which players can join the coalition. Table 5

Table 4
Classification of the reviewed works regarding decision-making strategies used to achieve fairness. The authors use two main categories of decision-making strategies and four sub-categories of mechanisms. The table presents the 80 works divided into different categories.

Strategy	Total	Mechanism	Total	References
Rule-based	29	Distribution	18	[10,24,27,36,40,46,52,57,59–61,72,75,84,89,95,97,102]
		Redistribution	11	[30,33,39,43,44,47,66,67,86,87,100]
Optimization	51	Objective function	32	[11,15,16,21–23,25,26,28,31,32,34,35,38,45,48,50,55,56,58,62–64,70,71,85,88,90,91,93,98,99]
		Constraints	19	[20,37,41,42,49,51,53,54,65,68,69,73,74,83,90,92,94,96,101]

Table 5
Economic and game theory concepts closely related to the consideration of fairness: The authors only consider concepts explicitly mentioned in the works analyzed. The table presents 30 entries; note that the same reference can include more than one of the concepts. A full table version is available in Table A.9 of the Appendix A.

Concepts	Total	References
Shapley value	11	[20,27,29,30,43,44,46,57,59,60,86]
Generalized nash game	10	[21,23,28,30,37,38,45,56,90,98]
Min-Max fairness	6	[36,41,54,73,74,94]
Supply and demand ratio	4	[20,69,85,93]

shows that 11 works utilize the SV, Ref. [60] introduces a payment distribution approach for demand response participation that utilizes the SV. Ref. [29] proposes a redistribution approach using the SV to distribute benefits among community members, considering the initial optimal portfolio solution obtained for the energy community. The SV is also used within optimization mechanisms, as demonstrated in [87], where it has been used to determine a fair coupon allocation strategy to enhance customers' willingness to participate in demand response programs.

The Generalized Nash Game (GNG) is the second most used concept in the analyzed literature, with 10 works using it as shown in Table 5. The GNG is used to find the best result for players in a game, considering that all players know the other players' strategies. Such a GNG is assumed to be fair, considering that each player can obtain the desired result at the equilibrium point if other players follow their initial strategies. In [30], a redistribution approach is introduced to achieve fair community cost sharing in the Nash equilibrium. Similarly, a Nash-type game with a linearization technique to improve computational efficiency is implemented and solved using an optimization mechanism in Ref. [21]. In this case, fairness in the trading is provided by developing a trading-aiding tool based on the Nash-type non-cooperative game.

Min-Max fairness is the next concept on the list, appearing 6 times in Table 5. This method uses a fairness criterion to distribute available resources among multiple users or entities to maximize the minimum share received/paid by any participant. In practical terms, Min-Max fairness allocates or distributes resources to different users to ensure each participant receives at least a specified minimum share. A Min-Max formulation is proposed in [73], where a distribution system operator aims to allocate flexibility costs fairly among aggregators.

Supply and Demand Ratio (SDR) (with 4 entries in Table 5) in fairness refers to the relationship between the availability of resources (supply) and the requests or needs (demand). In the context of fairness, this ratio is crucial in determining how resources are allocated and distributed among participants. The SDR ratio is applied in Ref. [20] as a criterion to determine the peer-to-peer energy sharing ratio. In this case, the ratio between supply and demand determines the quantity of energy shared (received or sent).

Table 6
Fairness indexes: The table presents indexes used in works considering fairness. A full table version with all found indicators is available in Appendix A as Table A.10.

Fairness indexes	Total	References	Formula[a]
Jain's fairness index	9	[11,47,51,65,68,70,83,97,101]	$JFI = \frac{(\sum_{i=1}^{N} EB_i)^2}{N \sum_{i=1}^{N} EB_i^2}$
F fairness index	4	[38,56,86,97]	$\mathcal{F} = \sum_{i=1}^{N} \left\| \frac{B_i}{\sum_{i=1}^{N} B_i} - \frac{S_i^*}{\sum_{i=1}^{N} S_i^*} \right\|$
K fairness index	2	[32,99]	$\mathcal{K} = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{EB_i}{Sh_i} - \frac{1}{N} \sum_{i=1}^{N} \frac{EB_i}{Sh_i} \right)^2$
Supply and Demand ratio	2	[15,62]	$SDR = \frac{\text{TSP}}{\text{TBP}}$
Participation index	2	[16,20]	$PI = \frac{N_{LowerCost}}{N}$

[a] Explanation of each variable of index formulas are presented in Appendix B.

5.3. Fairness indexes

So far, this work reviewed different approaches and concepts used to ensure fairness in LES. However, a complementary analysis made in this review is related to fairness indexes as metrics or tools used to quantify and evaluate the fairness of a process or system. Table 6 presents the indexes used in the analyzed literature.

A wide variety of indexes proposed in the literature measure fairness, such as Jain's Fairness Index (JFI), one of the most common indexes used to quantify the fairness of distributions or allocations. The JFI is obtained by dividing the squared of the sum of individuals' gains by the sum of the squared individual gains multiplied by the number of users. In practice, for resource allocation, the "individuals' gains" refer to the quantity of resources each user receives or benefits from. The JFI index is often used in works considering the equality fairness interpretation context, as presented in Refs. [47,65,70]. The value of JFI ranges from $\frac{1}{N}$ (N is the number of users) to 1, where a value closer to 1 indicates a fairer distribution, with users receiving an equal share of the gains. Considering the JFI helps to ensure that all community users receive a fair share of gains rather than having one user monopolize the shared gains. The JFI, identified in seven works, is commonly used to quantify the fairness of benefit distribution. The formula in Table 6 makes the calculation of the JFI highly suitable for ensuring fair and transparent distribution of economic profits, encompassing both costs and revenues among users. A smaller JFI value indicates greater disparities in the individual benefits received from the LEC market.

Another commonly used fairness index in the analyzed works is the $\mathcal{F}$ fairness index, which measures the distributions of gains of a given method compared to the ones obtained with the SV distributions. The $\mathcal{F}$ fairness index is frequently used for meritocracy fairness interpretation and appears in four works in the context of benefit distribution [38,56,86,97]. Looking at the formula in Table 6, the $\mathcal{F}$ index is calculated by considering the distance between a normalized billing vector when using any trading mechanism and the normalized billing vector obtained with the SV. Notice that this index assumes that the SV distribution is ideal, and a lower index value indicates that other distribution mechanisms are similar to the distribution obtained by SV.

According to Table 6, the $\mathcal{K}$ fairness index is applied to the benefit distribution scope and the DR context in two works. When $\mathcal{K} = 0$, it means that DR participants have shifted their load proportionally to their economic benefits. On the other hand, large values $\mathcal{K}$ indicate a disproportional allocation of resources.

The SDR, used in two works in Table 6, provides a perception of the total self-consumption within a group of users. Thus, the value of SDR can be used as an index indicating the surplus capacity of users in a community. A value of 1 indicates that the user has no surplus, greater than 1 indicates a surplus and less than 1 indicates no surplus. Therefore, the value of SDR can be related to the contribution of participants within a community and used as an auxiliary reference for benefit distribution.

Finally, the participation index (PI) in Table 6 is applied in two of the reviewed articles. Analyzing the formula, PI is a ratio between the number of users who obtain a lower cost with a given sharing mechanism compared to a baseline value (either from another distribution mechanism or an individual mechanism). Thus, a value near 1 represents a good distribution of benefits, as all participants are reducing their costs by joining the new sharing mechanism, while lower values indicate that most users are not reducing their baseline costs.

From the analyzed index applications in Table 6, most applications are related to the benefit distribution scope. However, JFI presents two applications in the (dis)comfort distribution scope.

5.4. Case studies examples from the literature

This subsection provides a few examples from the literature that illustrate the applicability of fairness concepts and indexes to LES as summarized in Table 6. The examples include applications in demand response, energy sharing and local trading, PV power curtailment, and reliability in distribution networks. This examples cover most of the LES applications and contexts that have been discussed in this review.

5.4.1. Demand response

Baharlouei et al. [38] proposed scalable autonomous DR by reducing utility control requirements. Each user will automatically adjust their flexible load depending on power pricing changes. Most autonomous DR studies have focused on coordinating flexible devices to minimize generating costs or load demand peak-to-average ratios but did not include fairness. Their work tackles previous shortcomings by proposing both optimality and fairness based on meritocratic principles. They have compared a benchmark test using a central DR system with their proposed smart electricity billing mechanism to enforce both aspects in a decentralized manner. Within the scope of their case study, 20 users are in the system, and their energy scheduling is optimized within the next 24 h. A random selection is made between 0 and 40 kWh for the total load of each user. The work uses the $\mathcal{F}$ fairness index as presented in Table 6 of this review. The simulation results show that using their proposed billing mechanism, the average $\mathcal{F}$ fairness index reduces from 0.171 to 0.046, a reduction of around 73%. A lower $\mathcal{F}$ index indicates a more fairer system. Their proposed billing mechanism is in the 1% of optimality gap compared to the benchmark reference, i.e., the proposed mechanism has less than 1% higher cost compared to the benchmark. Hence, it is concluded that there is a trade-off between fairness and optimality in the proposed case autonomous DR case.

Chen and Chang tackle fair DR with EVs in [16]. The formulation aims to maximize incentives and minimize global costs for each community. They propose meritocratic fairness as having lower costs for customers with higher level of participation in the DR. Hence, a specialized fairness index is formulated based on the participation levels, namely the customers' flexibility and their production capacity. This index is used to quantify the participation level and then utilized to customize the trading prices. The experimental setup compares the proposed method with a benchmark scenario without community trading and another without considering fairness. The communities are formed by involving customers with combinations of EV, PV and storage up to 1500 customers. Results indicate savings up to 18%.

Negash et al. in [99] implement the $\mathcal{K}$ fairness index as discussed in Section 5.3 to evaluate fairness for the case of allocation of the cost of DR in congested networks. Their sensitivity method is based on local marginal price, and they evaluate it on a use case considering a small 6-bus network. After the optimal power flow is run and the DR cost is determined for reducing 1% of the load, the DR cost is calculated to be 33.13$, which needs to be allocated and distributed to load buses. They depict the DR cost allocation using the proposed sensitivity method and a conventional one called load-based. The $\mathcal{K}$ fairness index is close to zero in the sensitivity-based proposal and 0.55 in the load-based method. This indicates that the proposed sensitivity-based method is more effective and fair at allocating DR costs.

5.4.2. Energy sharing and local trading

The study by Long et al. [86] presents a case study on a residential energy community with PV battery systems. The energy community comprises 10 prosumers, half with individual PV battery systems. The other half is without solar PV or batteries. The solar PV systems have 4 kWp production capacity, and the batteries have 4 kWh storage capacity with a maximum charging and discharging power of 4 kW. The price of the energy bought from the retail supplier is considered 0.15 £/kWh, and the price of energy exported to the grid is 0.05 £/kWh. The daily electricity bill of individual prosumers has been calculated using different schemes, including bill sharing (BS), MMR, SDR, and SV. The fairness of each scheme has been evaluated using the $\mathcal{F}$ fairness index. The SV method presented the lowest $\mathcal{F}$ value followed by MMR, SDR and BS. SV has allowed the most fair billing allocation among the tested billing schemes.

Zhou et al. presents a work [20] that focuses on energy-sharing mechanisms within Great Britain's current and future energy scenarios. The simulation framework evaluated and analyzed three energy sharing mechanisms, SDR, MMR, and BS, utilizing a multiagent-based simulation framework. The work considered other elements, such as varying levels of PV and EV adoption, different seasons, types of days, and retail price systems. In the study, the authors examined a sample of 20 residential households within a community. Each household considered flexible and inflexible equipment. The study has proposed an overall performance index that accounts for fairness aspects such as participation willingness, equality index, and value tapping. It has been possible to realize that energy sharing could improve technical and economic aspects. The findings indicated slight decreases in income equality for the SDR and MMR mechanisms compared to the conventional paradigm, suggesting that while these mechanisms offer overall benefits, they may result in somewhat uneven income distribution among participants. The SDR and MMR mechanisms generally showed high participation willingness, indicating that most participants found it beneficial to join these mechanisms. The SDR mechanism consistently outperformed the other mechanisms regarding overall benefits, followed by the MMR mechanism. Both SDR and MMR mechanisms have been found to tap into cost-saving potentials and enhance local energy balance and self-sufficiency. The SDR mechanism performed well across most scenarios, while the MMR mechanism performed well mainly in scenarios with moderate PV penetration levels. The BS mechanism generally did not offer significant benefits over the conventional non-P2P paradigm. In some scenarios, it even resulted in lower total incomes compared to the conventional paradigm.

5.4.3. Power curtailment

Liu et al. discusses the fairness of active power curtailment schemes for residential PV systems in [11]. The authors argue that existing curtailment schemes can be unfair, particularly Volt–Watt schemes, which penalize PV systems at remote locations in radial feeders. This is a challenging problem in distribution networks with high penetration of PV, and the issue is how to curtail PV power in a fair way if there is too much excess, i.e., which household should stop producing PV power. To assess fairness in this context, the authors propose three household-centric schemes to accurately quantify the impacts of PV curtailment schemes related to PV harvesting, energy export, and financial benefit. Authors adopt equality principles and use JFI to quantify how fair each scheme is and benchmark against established methods like the Volt–Watt scheme used in many operators worldwide. A scheme with a higher JFI is considered fairer. The JFI reaches its maximum value of 1 when all households receive the same benefit. The study uses a real Australian 22 kV feeder and realistically modeled LV networks with over 4500 households for a detailed comparison. The results show that all the schemes that consider fairness effectively remove locational penalizations compared to established benchmark methods.

Another research study [47] proposes a fairer control scheme also based on equality principles. The authors agree that Volt–Watt control

Table 7
Summary of JFI metric for PV curtailment case study [47].

Simulation	Description	JFI[a]	JFI[b]
A PV-rich LV grid	All houses have single-phase PV inverters with installed PV capacities of 3, 4, or 5 kWp, distributed randomly among the houses.	0.43	0.99
An LV grid with 55% PV penetration	This case study evaluated the impact of a different PV penetration level on the performance of the proposed strategy. 30 out of 55 houses have a PV system.	0.12	0.47

[a] (three-phase average) volt–watt and volt-var control.
[b] (three-phase average) proposed control.

schemes can lead to significant unfairness in the curtailed active power in PV-rich networks. They employ the JFI as a metric to assess the fairness of the curtailed active power among PV inverters. The work uses a case study based on the IEEE European Low Voltage Test Feeder, a 4-wire, 3-phase radial grid. The authors conducted five simulation case studies to evaluate the performance of their proposed decentralized control strategy in distribution networks with high penetration of PV. Table 7 summarizes the results obtained in their work for a PV rich Low Voltage (LV) and a LV grid with less PV penetration. JFI demonstrates that their proposed control scheme improves fairness in this context by allowing a more equal and fair power curtailment of PV power in households.

5.4.4. Reliability in distribution networks

The work from [52] studies electricity reliability in Norway, considering 19 counties, 117 network operators, and 36 consumer groups. The study interprets the fair relative reliability level as the national average reliability level. The authors use the Gini index and a variance-based index named coefficient of variation. Those indexes are less common in the analyzed papers and more specific to some application areas like reliability. By applying these specific indexes, the study finds that the Gini index varies between 0.24 and 0.49 in the 12 years of the study, and the Coefficient of variation varies between 0.7 and 0.99. There is no particular trend of the variation during the studied period as the reliability distribution policy in Norway is not used at the moment of the study. The study also finds that 4 of the lowest population density counties in the country have a 200% higher fairness ratio, meaning that energy not supplied is twice as much as the national average values in Norway. This work shows that fairness indexes are a simple and transparent way to evaluate reliability in power networks. It helps system stakeholders monitor fairness. The proposed fairness ratios can be used to assess the perceived fairness of specific entities (such as consumer groups or geographic regions) and identify the most affected ones. The study further discussed ways to directly reduce unfairness in energy not supplied, such as alternating affected customers over time, or indirectly, such as compensation schemes and reliability markets based on the fairness indexes.

6. Discussion and gaps in the literature

This review has classified the articles based on the context within LES and the interpretation of fairness according to classical views. Finally, each work's approaches to achieving fairness in each context have been classified. In this section, the authors depart from the earlier classification of the reviewed work to develop the present discussion.

Fig. 7 presents a Sankey diagram correlating the LES context and scope with the fairness principles adopted in this review. The analysis of Fig. 7 reveals that papers related to the LEC context mostly consider fairness from the benefit distribution perspective. In contrast, demand response works focus more on fairness related to comfort and pricing matters. The reviewed papers on fairness in LEC of microgrids fall exclusively in the benefit distribution category. Works in the scope of distribution networks tend to analyze the benefit distribution and some fairness issues related to comfort. Similarly, EV charging studies have fairness concerns related to comfort and pricing and less about benefit distribution. Interestingly, meritocracy fairness principles are mostly related to LEC and DR contexts. For example, the reviewed works in distribution networks only relate to equality principles.

According to the present review and the adopted classification in previous sections, Fig. 8 presents a Sankey diagram showing the relationship between fairness interpretation (Section 4.2), concepts (Section 5.2), and indicators (Section 5.3). It is important to highlight that many works do not explicitly present a concept or use a fairness indicator. The most applied concept is the SV, which is intrinsically related to meritocracy and thus unrelated to equality interpretation. Most studies using the SV do not apply a fairness indicator method to evaluate any dimension of fairness as SV it is widely accepted as a fair allocation method on its own. Analysis of this Sankey shows that the min–max concept is intrinsically related to the interpretation of min–max fairness, whereas the generalized Nash game is related to equality and meritocracy principles. "Other Concept" in the diagram corresponds to methods less common in the reviewed materials (a full list is available in Table A.9). Some papers do not identify or disclose the approach adopted for achieving fairness; thus, they fall into the "No concrete concept" category. JFI is the most used fairness indicator in the reviewed works. Many papers adopt novel or custom-based indicators, thus falling into the "Other Index" category in the presented Sankey diagram. Most of the works using SV, min–max and GNG do not present a fairness indicator.

A fairness indicator is a tool to assess and evaluate fairness in LES. Quantifying subjective perceptions into numerical metrics can be challenging, in part due to the lack of consensus on which indicators should be used and a clear definition of fairness, making it difficult to establish a universally accepted rule for assessing fairness. In the reviewed articles, it has been observed that authors usually focus on financial aspects, which are easier to quantify and measure than those related to human comfort or satisfaction.[4] The subjectivity of fairness perception, the need for justification and transparency, the computational complexity, and the diversity of fairness criteria in different contexts all contribute to the ongoing debate.

There are broader implications that can be sought from the studied literature for policymakers and practitioners. Fairness-enabled algorithms can guide the development of regulations and policies that promote fairness in LES. They can help identify areas where intervention is needed to ensure equitable access to energy resources. Furthermore, fairness indices can inform the design of incentives and subsidies to encourage the adoption of fair energy practices. Reviewed case studies and indices from the literature can help to identify best practices and strategies for achieving fairness in real-world settings. Moreover, they can provide a benchmark for evaluating the performance of energy services in terms of fairness. It is possible to summarize the challenges related to fairness implementation in LES in three dimensions, namely "subjectivity of fairness perception", "computational complexity", and "cost of fairness". One of the main challenges is to establish a universally accepted rule for assessing fairness. Not all the reviewed works adopt the same fairness metric and interpret fairness in the same manner. Another challenge is the computational complexity of some algorithms to ensure fairness in LES. Moreover, it is crucial to determine who will bear the cost of implementing fair algorithms and bear added computational requirements. Developing frameworks and guidelines that consider multiple perspectives and dimensions of fairness can

[4] Less than 30% of the reviewed works are related to comfort or satisfaction.

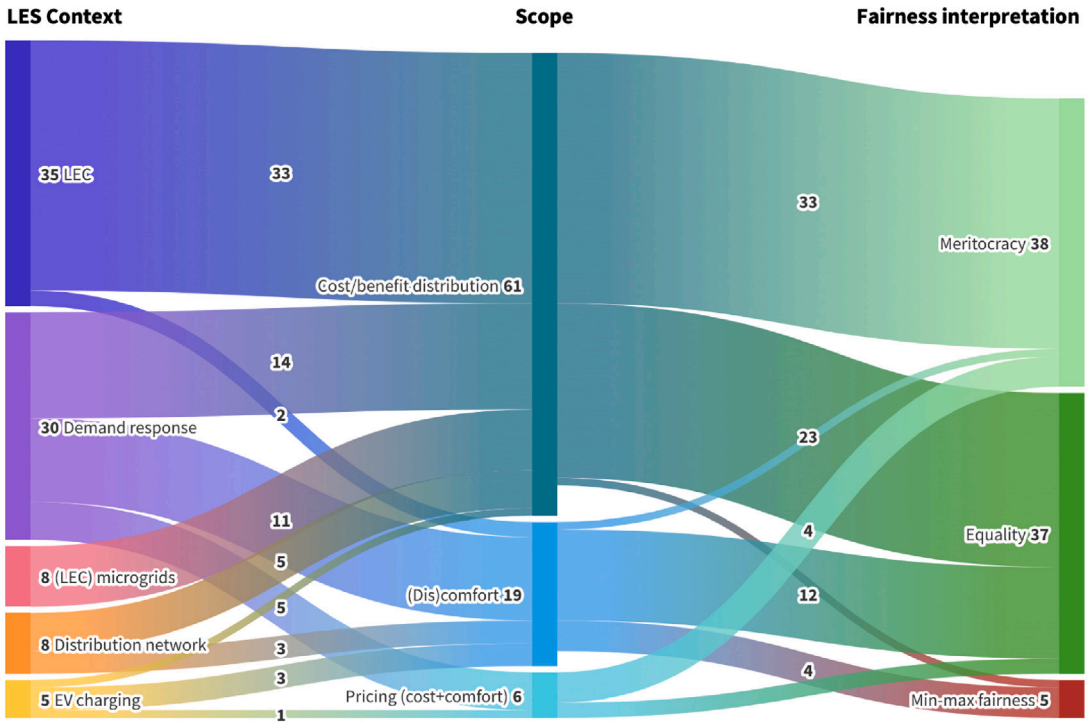

Fig. 7. The Sankey diagram shows the relationship between the context and scope and the fairness principles adopted in the reviewed works. The quantities indicate the number of papers classified in each category, with some papers falling into more than one context/scope category. For visual simplicity, only the main fairness interpretation category is selected.

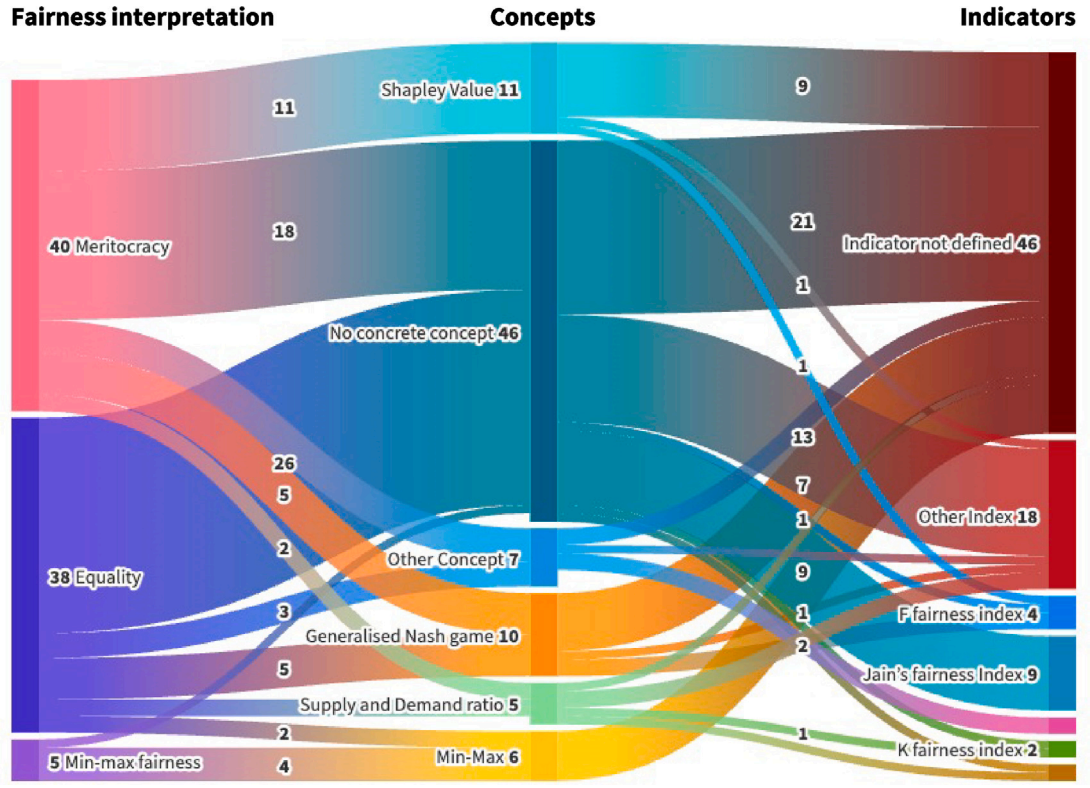

Fig. 8. The Sankey diagram shows the relationship between the fairness interpretations, concepts, and indicators presented in the reviewed works. Some papers fall into more than one concept. As a result, there are more concepts compared to the actual number of works.

aid in evaluating and designing fair LES. Still, quantifying subjective perceptions remains a subject of ongoing research and discussion.

The computational complexity of game-based methods to ensure fairness in LES requires balancing computational effort without compromising responsiveness. The impact of fairness considerations on LES algorithms' performance and the amount of additional computing energy required has not yet been thoroughly discussed in the literature. This significant gap has been identified in this review, and future research is recommended to address the identified limitations. Furthermore, it is necessary to determine who will bear the cost of the increased computational requirements needed to incorporate fairness into the new algorithms proposed. Implementing fair solutions should be cost-effective, but this is still uncertain and not well-assessed in current works. It may be worthwhile to investigate whether government agencies and other organizations are willing to provide funding for initiatives to promote fairness in LES and enable new standards. Energy companies and private ventures may encounter difficulties in developing "fair" algorithms, as there may be limited and unpredictable returns on the investment to provide fairer algorithms; nevertheless, some of these costs may initially be transferred to end-users or consumers. Ultimately, fairer energy systems are expected to yield economic savings, social advantages, and improved environmental sustainability [20,32,92]. Additionally, these systems have the potential to positively impact underprivileged communities, leading to savings, improved health, preservation of biodiversity, and a cleaner environment [105,106]. Continued research and discussion on this topic are essential to advance the field and contribute to a more equitable energy transition.

7. Conclusions

This review summarized the main body of existing literature on algorithms and approaches considering fairness aspects for the LES domain, showing that fairness is gaining attention in the LES context, especially since 2017 (cf. Fig. 1). Fairness implications in LES can vary significantly according to context, demographics, and region. For instance, ensuring fairness may not be effective in every context. Similarly, the fairness of an algorithm may impact diverse groups differently. According to the current literature, this complex dimension of algorithmic fairness presents an ongoing and major challenge. The concept of fairness in energy systems holds substantial significance, yet a consensus on its definition remains elusive. Developing a framework or guidelines considering different perspectives is crucial to determining fairness in LES. Being subjective, fairness perception poses challenges in quantification and measurement. However, current research work can justify their perspectives on fairness by leveraging approaches like the SV. Transparency and justification are essential when labeling "fair" energy system functions, as insufficient clarity can undermine the credibility of fairness claims, necessitating the provision of plain explanations and empirical evidence supporting such labels. Summarizing the main gaps identified and that require further research are:

- Investigating on how and who pays for adding fairness aspects in new algorithms;
- Estimates to assess the additional cost of including fairness and the methods to determine the scenarios and the impact of neglecting fairness;
- Understanding of how fairness impacts new algorithms in terms of performance;
- Development of new standards to define what is fair in the LES context and what are the essential fairness aspects;
- Development of appropriate evaluation metrics and benchmark tests for enabling energy algorithms comparison in the LES domain;
- Increased transparency of energy algorithms to increase acceptability. Explainability of algorithms can help to achieve this;

The first systematic review of the literature on fairness in LES has been provided; this paper has made significant steps to understand and advance knowledge in this field. It has consolidated and analyzed existing research, providing a new foundation for further research.

CRediT authorship contribution statement

João Soares: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Fernando Lezama:** Writing – original draft, Visualization, Validation, Investigation. **Ricardo Faia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology. **Steffen Limmer:** Writing – review & editing, Writing – original draft, Supervision. **Manuel Dietrich:** Writing – review & editing, Writing – original draft, Investigation. **Tobias Rodemann:** Writing – review & editing, Supervision, Conceptualization. **Sergio Ramos:** Writing – review & editing, Project administration. **Zita Vale:** Writing – review & editing, Validation, Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Joao Soares reports financial support was provided by Honda Research Institute Europe GmbH. If there are other authors, they 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

No data was used for the research described in the article.

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Appendix A. Supplementary tables

See Tables A.8–A.12.

Appendix B. Supplementary index formulas

Jain's fairness index:

$$JFI = \frac{(\sum_{i=1}^{N} EB_i)^2}{N \sum_{i=1}^{N} EB_i^2} \tag{B.1}$$

where N is the number of users and EB_i represents the economic benefits of each user i, and is obtained with $C_i^e - C_i^{ref}$, the difference with energy costs with C_i^e and without C_i^{ref} participation in shared economy.

F fairness index:

$$\mathcal{F} = \sum_{i=1}^{N} \left| \frac{B_i}{\sum_{i=1}^{N} B_i} - \frac{S_i^*}{\sum_{i=1}^{N} S_i^*} \right| \tag{B.2}$$

Table A.8
Context and scope of the analyzed literature.

Context	Scope			
	Benefit distribution	(Dis)comfort	Pricing	Total
LECs	[10,15,16,20,21,26–34,62,63,65–68,83–86,89,90,92–94,97,100–102]	[22,23]		35
Demand response	[16,37–39,56–60,85,87,93,99,100]	[35,36,41,42,69–73,91,95]	[24,25,40,61,75]	30
(LEC) Microgrid	[43–46,64,88,96,98]			8
Distribution network	[11,47–50]	[51,52,95]		8
EV charging	[54]	[53,71,74]	[55]	5
Total	61	19	6	

Table A.9
Full version of Table 5.

Concepts	Total	References
Shapley value	11	[20,27,29,30,43,44,46,57,59,60,86]
Generalized Nash game	10	[21,23,28,30,37,38,45,56,90,98]
Min-Max fairness	6	[36,41,54,73,74,94]
Supply and demand ratio	4	[20,69,85,93]
Bill sharing	2	[20,31]
Mid-Market rate	2	[20,31]
Nash bargaining	1	[88]
Core Tâtonnment	1	[15]
Min variance	1	[62]
Shapley-Core	1	[32]
Shapley-Nucleolus	1	[32]
Min-Variance-Nucleolus	1	[32]
Nucleolus	1	[63]

Table A.10
Full version of Table 6.

Fairness indexes	Total	References
Jain's Fairness Index (JFI)	9	[11,47,51,65,68,70,83,97,101]
F fairness index	4	[38,56,86,97]
K fairness index	2	[32,99]
Supply and demand ratio	2	[15,62]
Participation index	2	[16,20]
Nash social welfare	1	[23]
Quality of service	1	[92]
Quality of experience	1	[92]
Min-Max indicator	1	[92]
Retailers willingness ratio	1	[54]
Value tapping	1	[20]
Equality index	1	[20]
Gini-based	1	[52]
Variance-based fairness index	1	[52]
Shapley value-based index	1	[58]
Unfairness index	1	[72]
Coalition stability test	1	[32]
Output-input ratio	1	[85]
Behavioral reciprocity	1	[24]
Discomfort standard deviation	1	[71]
Fairness factor	1	[61]
Ad-hoc[a]	4	Equation (12) from [25], (14) from [100], (18) from [53] and (26) from [75]

[a] These works present a fairness index without a specific name. The authors of the paper included the respective equation from the related reference.

where B_i is the bill or income of prosumer i when using other trading mechanisms and S_i^* is the bill or income of prosumer i when using the SV.

K fairness index:

$$\mathcal{K} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{EB_i}{Sh_i} - \frac{1}{N}\sum_{i=1}^{N}\frac{EB_i}{Sh_i}\right)^2 \tag{B.3}$$

Table A.11
Type of mathematical optimization problem.

Strategy	Optimization	
Mechanism	Objective function	Constraint
Mathematical optimization problem	MILP [21,25,35], NL [64], Nash bargaining problem [88], LP [15], NL dynamic system [45], bi-level programming model [93], ILP [16]	MILP [41,53,68,90,94,96], SOCP [49], bi-level programming model [54], LP [20]

Table A.12
Game-theory approaches.

Strategy	Mechanism	Cooperative	Non-cooperative
Rule-based	Distribution	[27,59,89,97]	[102]
	Redistribution	[29,66,67]	[87]
Optimization	Objective function	[15,23,28,32,58,63]	[11,21,32,38,45,56,88,98]
	Constraints	[54,90]	[37]

where Sh_i is the is total energy of load shifting (kWh) of prosumer i, and is obtained considering the $\frac{\sum_{h=1}^{H}|TP_i^h - x_i^h|}{2}$, where TP_i^h is the deviation from the original value x_i^h.

Supply and demand ratio:

$$SDR = \frac{TSP}{TBP} \tag{B.4}$$

where TSP is the total selling power and TBP is the total buying power.

Participation index:

$$PI = \frac{N_{LowerCots}}{N} \tag{B.5}$$

where $N_{LowerCots}$ represents the number of users who have lower energy cost with shared economy.

Appendix C. Key works selection

The selection of the key works has been done considering the number of citations (as of May 10, 2024, according to Google Scholar), the citations per year, and the impact factor (2023). All ranks in Table C.13 are numbered between 1 and 80. The Score rank is obtained after applying Eq. (C.1). The two highest-ranked works for each scope have been selected.

$$\begin{aligned} Score =& (0.4 \times \text{Citation rank}) + (0.3 \times \text{Citation per year rank}) \\ &+ (0.3 \times \text{Impact factor rank}) \end{aligned} \tag{C.1}$$

Table C.13
Key works rank.

Ref.	Scope	Citations	Citation rank	Citation per year	Citation per year rank	Impact factor	Impact factor rank	Score	Score rank
[20]	Benefit distribution	433	3	75	3	11.2	3	3.00	1
[21]	Benefit distribution	178	6	45	5	11.2	4	5.10	2
[22]	(Dis)comfort	84	18	28	11	11.2	7	12.60	7
[23]	(Dis)comfort	80	19	20	20	11.2	11	16.90	12
[24]	Pricing	51	39	10	42	6.3	52	43.80	43
[25]	Pricing	59	32	5	62	–[a]	73	53.30	56

[a] Conference paper without impact factor.

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