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A Review and Future Research Agenda for Justice-Aware Smart-Grid Optimization: Energy Equity, Algorithmic Governance, and Low-Carbon Flexibility Markets

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Abstract

Smart-grid optimization increasingly uses artificial intelligence, automated control, and data-driven market coordination to manage low-carbon electricity systems. These developments create new opportunities for flexibility, but they also raise unresolved questions about equity, accountability, and justice. Existing reviews often examine energy justice, smart-grid optimization, algorithmic governance, and flexibility markets as separate domains. This fragmentation limits understanding of how optimization models and market rules may reproduce or reduce social inequalities. This article critically reviews the literature on justice-aware smart-grid optimization and develops a structured future research agenda. It focuses on how energy equity, algorithmic governance, and low-carbon flexibility markets can be integrated into future smart-grid research and policy. A targeted review of 26 peer-reviewed articles published between 2017 and 2025 integrates perspectives from energy justice, smart-grid studies, AI governance, and electricity market design. The review identifies conceptual tensions, methodological gaps, and governance challenges rather than presenting new empirical data. The review shows that justice is often operationalized narrowly in optimization, while broader concerns about recognition, participation, and accountability remain underdeveloped. It also finds that flexibility markets can distribute benefits unevenly unless market design explicitly addresses barriers to access and agency. A more interdisciplinary and justice-centered approach is needed to guide smart-grid optimization. The proposed agenda calls for stronger integration between technical modeling, energy justice theory, participatory governance, and regulatory innovation.

Keywords Smart grid, Justice-aware optimization, Energy equity, Algorithmic governance, Low-carbon flexibility markets, Research agenda

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Introduction

Smart-grid optimization is increasingly central to the governance of low-carbon electricity systems because it coordinates distributed energy resources, flexible demand, and network constraints in real time. Yet optimization is not socially neutral, since the allocation of costs, benefits, risks, and decision rights can shape who gains from the energy transition and who remains exposed to vulnerability. Energy justice scholarship has therefore become essential for interpreting smart-grid design, especially where affordability, access, and recognition are affected by automated grid decisions [1]. This review starts from the premise that justice-aware optimization must be understood as both a technical and socio-political project.

The literature on energy justice provides a mature vocabulary for distributive, procedural, and recognition-based concerns, but it has not always been translated into optimization models or market-clearing mechanisms. Heffron and McCauley argue that energy justice crosses disciplinary boundaries, yet smart-grid optimization often narrows justice to measurable constraints rather than institutional accountability or democratic participation [2]. McCauley, Ramasar, Heffron, Sovacool, Mebratu, and Mundaca further show that low-carbon transitions require attention to interdisciplinary justice themes, which suggests that algorithmic systems must be evaluated beyond efficiency and decarbonization metrics [3]. This creates a need for review work that connects justice concepts to the formal design of smart-grid decisions.

At the same time, digitalization has expanded the role of artificial intelligence, forecasting, platform coordination, and local markets in electricity systems. Powells and Fell's concept of flexibility justice is particularly important because it reframes flexibility not only as a resource for system balancing but also as a capacity unevenly distributed across households and communities [4]. Calver and Simcock show that demand response can generate ethical risks when digital, decentralized, and decarbonized energy futures rely on participation that not all consumers can provide equally [5]. These insights indicate that justice-aware smart-grid optimization must address both model outputs and the social conditions under which flexibility is produced.

This article contributes by critically synthesizing energy justice, algorithmic governance, and low-carbon flexibility market scholarship into a research agenda for justice-aware smart-grid optimization. Rather than treating fairness as an add-on constraint, it examines how equity principles can influence problem formulation, data selection, market access, algorithmic accountability, and regulatory oversight. The review builds on work showing that smart-grid experiments and digital energy infrastructures embody contested social values, not merely technical preferences [6]. Its central argument is that future smart-grid optimization should be designed as an accountable socio-technical system capable of recognizing vulnerability, enabling participation, and distributing flexibility benefits fairly.

Justice-Aware Optimization Scope

Defining justice-aware optimization

Justice-aware optimization refers to the deliberate embedding of fairness, equity, recognition, and accountability principles into the objectives, constraints, data practices, and governance arrangements of smart-grid decision systems. In contrast to conventional optimization, which often prioritizes least-cost dispatch, system reliability, or emissions reduction, a justice-aware approach asks whether the model distributes burdens and benefits fairly across differentiated social groups. Jenkins, McCauley, and Forman's policy-oriented account of energy justice supports this shift by emphasizing that justice must be operationalized across decision-making processes, not simply invoked as a normative aspiration [1]. In smart grids, this means that fairness must be considered before optimization begins, not only after outputs are produced.

Scope and boundaries

The scope of justice-aware smart-grid optimization includes fairness-constrained dispatch, equitable demand response, local flexibility markets, aggregator coordination, explainable AI, and participatory forms of energy governance. It excludes purely technical optimization that has no explicit concern for distributional outcomes, procedural inclusion, recognition of vulnerable users, or accountability for algorithmic decisions. Milchram, Hillerbrand, van de Kaa, Doorn, and Künneke demonstrate that smart-grid systems involve moral choices in design, suggesting that boundaries between engineering and governance are porous rather than fixed [6]. This review therefore treats optimization models, digital platforms, and market rules as connected sites where justice can be advanced or undermined.

Current approaches and limitations

Current approaches tend to operationalize justice through fairness indicators, priority weights, compensation rules, or participation constraints, but these techniques often remain weakly connected to the broader institutional conditions of energy vulnerability. Fairness work in local energy systems has advanced the measurement of distributional outcomes, yet Soares, Lezama, Faia, Limmer, Dietrich, Rodemann, Ramos, and Vale show that fairness concepts vary widely and may not capture procedural or recognition justice [7]. Similarly, emergency demand response algorithms can improve allocation fairness, but Jacubowicz, Raz, and Beck illustrate that such tools remain bounded by technical assumptions about controllability and user responsiveness [8]. The limitation is not that optimization cannot support justice, but that it often simplifies justice into variables that are easier to compute than to govern.

Energy Equity Concepts

Distributive, procedural, and recognition justice

Energy equity in smart-grid optimization is most commonly framed through distributive justice, procedural justice, and recognition justice. Distributive justice concerns how costs, benefits, reliability impacts, and flexibility revenues are allocated, while procedural justice concerns who participates in rule-making and contestation of algorithmic outcomes. Recognition justice requires attention to groups whose needs, histories, or capacities may be overlooked by standardized smart-grid models, a concern emphasized in the wider energy justice literature [2]. For optimization, these principles imply that fair outcomes cannot be separated from fair processes and accurate recognition of differentiated users.

Energy vulnerability and inclusion

Energy vulnerability is central to justice-aware optimization because flexibility markets and demand response programs often assume that users have digital access, controllable appliances, financial security, and time flexibility. Fjellså, Silvest, and Skjølsvold show that flexible household electricity consumption raises justice questions when households differ in their ability to shift demand or absorb inconvenience [9]. Calver and Simcock similarly warn that demand response can amplify inequities when vulnerable users face stronger pressure to adapt their behavior while receiving fewer benefits [5]. Inclusion therefore requires more than open enrollment; it requires market and model designs that recognize unequal capacities to participate.

Equity metrics and quantification

Equity metrics translate justice principles into measurable indicators, but quantification can narrow the meaning of justice when it privileges outcomes that are easiest to model. Dyrge and Cali's work on distributive energy justice in local electricity markets shows the value of fairness indicators for assessing market outcomes, while also highlighting that indicator choice shapes what counts as fair [10]. Reviews of fairness in local energy systems similarly demonstrate that metrics may address allocation, envy, proportionality, or welfare, yet they do not automatically capture power relations or voice [7]. Smart-grid optimization therefore needs reflexive metric design that makes normative assumptions explicit rather than hiding them inside mathematical formulations.

Application in grid optimization

Applying energy equity concepts in grid optimization requires linking justice principles to specific modeling decisions such as objective functions, constraints, user segmentation, compensation rules, and acceptable trade-offs. Milchram, Künneke, Doorn, van de Kaa, and Hillerbrand show that smart-grid experiments can be designed with justice considerations, but they also reveal how institutional context affects whether ethical principles influence implementation [11]. **Table 1** summarizes major equity frameworks and indicates how each can be operationalized in smart-grid optimization without reducing justice to a single fairness score. The table also highlights that the strongest justice-aware approaches combine distributive metrics with participatory governance and recognition-sensitive data practices.

Table 1. Comparative Overview of Equity and Justice Frameworks in Smart-Grid Optimization and Their Operationalization Pathways

Framework or concept	Key justice principle	Relevance for smart-grid optimization	Operationalization pathway	Critical limitation
Energy justice policy approach	Distribution, procedure, recognition	Positions optimization as a policy-relevant allocation mechanism	Include affordability, participation, and vulnerability constraints in model design	Risks becoming rhetorical if not tied to enforceable rules
Interdisciplinary energy justice	Cross-disciplinary justice integration	Connects technical optimization with social transition analysis	Combine engineering objectives with social-science evaluation criteria	Difficult to translate fully into formal model structures
Flexibility justice	Unequal capacity to provide demand-side flexibility	Reveals that flexibility is not equally available to all users	Weight participation burdens and compensate inconvenience asymmetrically	Can be hard to measure without household-level data
Demand-response ethics	Fair access, consent, and protection from harm	Evaluates automated load shifting and behavioral incentives	Require opt-out rights, transparent incentives, and protections for vulnerable users	May conflict with system operators' desire for predictable response
Distributive market fairness	Allocation of benefits and burdens	Assesses local market revenues, network charges, and curtailment impacts	Use fairness indicators alongside welfare and efficiency measures	Indicator choice may obscure procedural and recognition concerns
Justice-by-design smart grids	Embedded values in infrastructure design	Treats smart-grid architecture as a moral and institutional design problem	Integrate justice criteria during pilot design, procurement, and evaluation	Requires governance capacity beyond technical modeling

Algorithmic Governance

AI governance in critical infrastructure

Algorithmic governance in smart grids concerns how automated systems are authorized, monitored, explained, challenged, and corrected when they affect electricity access, affordability, reliability, or market participation. Because electricity systems are critical infrastructure, AI-based optimization cannot be governed as ordinary consumer software; it requires higher standards of reliability, accountability, and public legitimacy. Noorman, Espinosa Apráez, and Lavrijssen argue that AI and energy justice must be considered together because algorithmic energy systems can create new forms of exclusion and responsibility gaps [12]. Justice-aware optimization therefore depends on governance arrangements that specify who is answerable when automated grid decisions disadvantage particular users.

Transparency, explainability, and contestability

Transparency and explainability are necessary but insufficient conditions for justice-aware smart-grid optimization. Machlev, Heistrene, Perl, Levy, Belikov, Mannor, and Levron show that explainable artificial intelligence techniques can improve interpretability in energy and power systems, yet technical explanations do not automatically create meaningful contestability for affected communities [13]. Contestability requires that users, aggregators, regulators, or community

representatives can challenge decisions, request review, and obtain remedies when algorithmic outcomes are harmful or unfair. Thus, explanation must be connected to procedural rights rather than treated as a purely technical feature.

Accountability and liability

Accountability becomes complicated in smart-grid optimization because decisions may be distributed across model developers, data providers, aggregators, distribution system operators, retailers, and regulators. El-Haber, Burnett, Halford, Stamp, De Silva, Manic, and Jennings propose a lifecycle approach to AI ethics in energy systems, which is useful because responsibility must extend from design and deployment to monitoring and revision [14]. However, lifecycle ethics must still confront liability when optimization errors or biased market rules produce unequal costs or service quality. Justice-aware governance therefore requires traceable decision records, clear accountability chains, and enforceable obligations for actors who benefit from algorithmic coordination.

Gaps in energy-specific governance

A key gap is that general AI governance principles are often not adapted to the institutional specificity of electricity networks, market regulation, and household energy vulnerability. Omitaomu and Niu's survey of artificial intelligence techniques in smart grids illustrates the breadth of technical applications, but it also shows why governance frameworks must keep pace with increasingly complex optimization and prediction systems [15]. Delina and Tung argue that just AI-assisted energy transitions require specific attention to vulnerable communities, which strengthens the case for governance models grounded in energy justice rather than generic AI ethics [16]. Without energy-specific governance, algorithmic smart grids may be technically efficient while remaining socially opaque and politically under-accountable.

Low-Carbon Flexibility Markets

Market design and participation

Low-carbon flexibility markets are designed to mobilize distributed resources such as demand response, storage, electric vehicles, heat pumps, and prosumer generation to support decarbonized grid operation. Jin, Wu, and Jia show that local flexibility markets vary in concepts, models, and clearing methods, which means that participation rules and settlement mechanisms can shape who is able to benefit [17]. Market design is therefore not only a technical matter of clearing efficiency but also a justice issue involving access, representation, and the distribution of opportunity. A justice-aware review must ask whether flexibility markets reward those already equipped with capital and technology while leaving vulnerable users as passive cost bearers.

Justice implications of market access

Access to flexibility markets depends on digital infrastructure, asset ownership, data literacy, contract terms, and the ability to tolerate shifts in consumption or comfort. Tsousoglou, Giraldo, and Paterakis review local electricity market mechanisms and show that design choices such as bidding rules, pricing schemes, and coordination architectures influence participation and welfare allocation [18]. These mechanisms can unintentionally favor larger or better-resourced actors when transaction costs, technical requirements, or aggregator dependencies are high. Justice-aware market access therefore requires attention to both formal eligibility and the practical conditions that make participation feasible.

Distribution of benefits and burdens

The distribution of benefits and burdens in flexibility markets includes revenues from flexibility provision, exposure to dynamic prices, network cost allocation, privacy risks, and the inconvenience of demand shifting. Tsousoglou, Giraldo, Pinson, and Paterakis explicitly address fair and efficient distribution system operator flexibility markets, showing that mechanism design can incorporate fairness while still supporting operational objectives [19]. Yet fairness mechanisms must be scrutinized for whose welfare is represented and whether vulnerable users receive protection or merely

compensation after burdens are imposed. Justice-aware optimization should therefore evaluate not only aggregate gains but also the social patterning of losses, risks, and obligations.

Aggregators and prosumer agency

Aggregators can expand flexibility participation by pooling small-scale resources, but they can also concentrate decision power and mediate prosumer agency through opaque contracts or automated control. Sareen, Smith, Gantioler, Balest, Brisbois, Tomasi, Sovacool, Torres Contreras, DellaValle, and Haarstad argue that digitalized and decarbonized energy infrastructures have important social implications, including changes in control, agency, and dependency [20]. **Table 2** maps justice issues to specific flexibility market design features and shows that aggregators should be assessed not only as efficiency-enhancing intermediaries but also as governance actors. This perspective reframes prosumers as rights-bearing participants whose consent, data, compensation, and contestability must be designed into market systems.

Table 2. Justice Dimensions in Flexibility Market Design and Governance-Oriented Operational Responses in Smart-Grid Systems

Market design feature	Justice issue	How inequity may arise	Examples from the literature	Justice-aware design response
Eligibility requirements	Recognition and access	Users without smart devices, storage, or flexible loads are excluded	Flexibility justice emphasizes unequal capacity to provide flexibility	Create low-threshold participation routes and support vulnerable users
Dynamic pricing	Distributional fairness	Low-income households may face higher exposure to price volatility	Demand-response ethics identifies affordability and risk-shifting concerns	Add bill protection, default safeguards, and targeted compensation
Market clearing algorithm	Procedural and distributive justice	Efficiency-maximizing clearing can ignore unequal welfare effects	Fair DSO flexibility market design integrates fairness with efficiency	Include fairness constraints and publish contestable clearing rules
Aggregator contracts	Agency and accountability	Users may lose control over devices or lack meaningful consent	Digital energy infrastructure studies highlight changing control relations	Require transparent contracts, opt-out rights, and auditability
Data requirements	Privacy and recognition	Granular household data can expose sensitive behavior patterns	AI-energy justice work links data systems to vulnerability and exclusion	Adopt data minimization, explainability, and community oversight
Settlement and compensation	Benefit distribution	Rewards may flow mainly to asset-rich prosumers	Local electricity market reviews show design-dependent welfare allocation	Use equity-weighted payments and monitor distributional outcomes

Critical Debates

Efficiency vs. equity

A central debate in justice-aware smart-grid optimization concerns whether equity can be incorporated without undermining efficiency, reliability, or decarbonization objectives. Fair flexibility market design shows that fairness and efficiency need not be mutually exclusive, but Tsaousoglou, Giraldo, Pinson, and Paterakis demonstrate that the balance depends on the mechanism used to clear markets and allocate payments [19]. The deeper problem is that efficiency is often treated as technically objective, while equity is treated as a secondary social correction. Justice-aware optimization challenges this hierarchy by arguing that efficiency itself is politically constructed when models decide whose costs, comfort, and risks are counted.

Technology-centric vs. socio-technical approaches

Another debate concerns whether smart-grid optimization should be treated primarily as a technical improvement or as a socio-technical transformation. Kumar's critique of smart grids in India shows that technical smartness can obscure local social relations, institutional capacities, and uneven development conditions [21]. Hargreaves, Hargreaves, and Chilvers similarly show that smart energy futures contain diverse stakeholder perspectives, meaning that there is no single public meaning of a socially smart grid [22]. The implication is that justice-aware optimization cannot be developed only through better algorithms; it also requires attention to the political, cultural, and institutional settings in which algorithms operate.

Participation and digital exclusion

Participation is frequently celebrated in demand response and flexibility markets, but digital participation can exclude users who lack devices, data literacy, trust, time, or control over household energy practices. Tarasova and Rohrer argue that household users can be marginalized in smart-grid development, especially when design assumptions privilege technically capable or economically rational participants [23]. This critique is reinforced by flexibility justice scholarship, which shows that users differ in their capacity to respond to price signals or automated control [4]. The debate is therefore not whether participation is desirable, but whether participation is meaningful, accessible, and protected from becoming a new obligation imposed on vulnerable users.

The role of regulation

Regulation is often positioned as an external constraint on innovation, yet justice-aware smart-grid optimization requires regulation as a constitutive design force. Jenkins, Stephens, Reames, and Hernández argue that impactful energy justice research must transform the power of academic engagement, which implies stronger links between research, regulation, and public accountability [24]. AI-enabled energy systems also require governance mechanisms that clarify accountability, transparency, and contestability before harms occur, not only after algorithmic failures become visible [12]. The critical debate is therefore whether regulators will merely approve technical market innovations or actively shape them around equity, recognition, and democratic oversight.

Research Gaps

Empirical evidence gap

Although this article does not present new empirical data, the reviewed literature reveals a gap in evidence about how justice-aware optimization performs in real institutional settings. Milchram, Künneke, Doorn, van de Kaa, and Hillerbrand show that smart-grid experiments can expose justice concerns, but such experiments remain limited in scale, geography, and transferability [11]. Dynge and Cali provide indicators for distributive energy justice in local electricity markets, yet more work is needed to understand whether these indicators alter market behavior or regulatory decisions [10]. Future research must therefore connect conceptual justice claims to observed outcomes without reducing justice to purely quantitative evaluation.

Methodological pluralism

A second gap concerns methodological pluralism, because optimization studies, AI ethics work, and energy justice scholarship often use different assumptions about evidence, validity, and social value. Iwińska, Lis, and Mączka identify gaps and critical trends in global energy justice research, suggesting that framework development alone is insufficient unless it is linked to grounded and interdisciplinary inquiry [25]. Explainable AI techniques can improve technical interpretability, but Machlev, Heistrene, Perl, Levy, Belikov, Mannor, and Levron show that explanation methods must still be adapted to domain-specific uses in energy and power systems [13]. Justice-aware optimization therefore needs mixed conceptual, participatory, legal, and technical methods that can examine both model behavior and lived consequences.

Cross-sectoral and comparative research

A third gap concerns comparative and cross-sectoral research across electricity, heating, mobility, housing, and digital infrastructure. Sareen, Smith, Gantioler, Balest, Brisbois, Tomasi, Sovacool, Torres Contreras, DellaValle, and Haarstad show that digitalization and decarbonization reshape energy infrastructure in ways that extend beyond electricity markets alone [20]. Delina and Tung's work on just AI-assisted energy transitions further indicates that vulnerable communities experience algorithmic energy systems through broader social, economic, and infrastructural conditions [16]. Comparative research is needed to examine how justice-aware optimization varies across countries, regulatory regimes, community contexts, and low-carbon technologies.

Future Research Agenda

Operationalizing justice in optimization models

Future research should develop optimization models that treat justice as a core design principle rather than an ex post evaluation criterion. Fairness indicators reviewed by Soares, Lezama, Faia, Limmer, Dietrich, Rodemann, Ramos, and Vale offer a starting point, but they should be combined with recognition-sensitive categories and participatory processes for defining what fairness means in context [7]. Emergency demand response work by Jacubowicz, Raz, and Beck shows that algorithmic fairness can be embedded in operational decisions, but future models must also address consent, vulnerability, and accountability [8]. A key research direction is therefore to build models that make trade-offs visible and allow affected groups to contest the justice assumptions built into objective functions and constraints.

Integrating governance and market design

Future research should integrate algorithmic governance with flexibility market design rather than treating them as separate policy domains. Jin, Wu, and Jia show that local flexibility markets differ substantially in architecture and clearing methods, while lifecycle AI ethics research demonstrates that governance obligations must span design, deployment, monitoring, and revision [14, 17]. This suggests that market rules should include auditability, explanation, liability, and appeal mechanisms from the beginning. Research should examine how regulators can require fairness impact assessments for market-clearing algorithms and aggregator platforms before they are deployed at scale.

Community-centered and participatory research

A justice-aware agenda must move beyond modeling representative consumers toward community-centered and participatory research. Jenkins, Stephens, Reames, and Hernández emphasize that impactful energy justice research requires transforming relationships between researchers and affected communities, which is particularly relevant for AI-enabled grid systems [24]. Hargreaves, Hargreaves, and Chilvers show that smart energy futures are contested by stakeholders, making participatory design essential for defining legitimate optimization goals [22]. Future studies should therefore co-produce justice metrics, data governance rules, and flexibility participation models with communities that are often treated as passive demand-side resources.

Policy and regulatory experiments

Future research should also examine policy and regulatory experiments that test justice-aware optimization under real governance constraints. Guasselli’s analysis of AI-driven energy futures shows that industry imaginaries can strongly shape expectations about digital energy systems, making it important to evaluate whose futures are being optimized [26]. Noorman, Espinosa Apráez, and Lavrijssen connect AI and energy justice in ways that support experimentation with contestability, rights-based oversight, and accountability frameworks [12].

Figure 1 presents the proposed justice-aware smart-grid optimization pathway, showing how equity concepts, algorithmic governance mechanisms, and low-carbon flexibility market design can be integrated into a socio-technical research agenda for accountable and inclusive smart-grid decision-making.

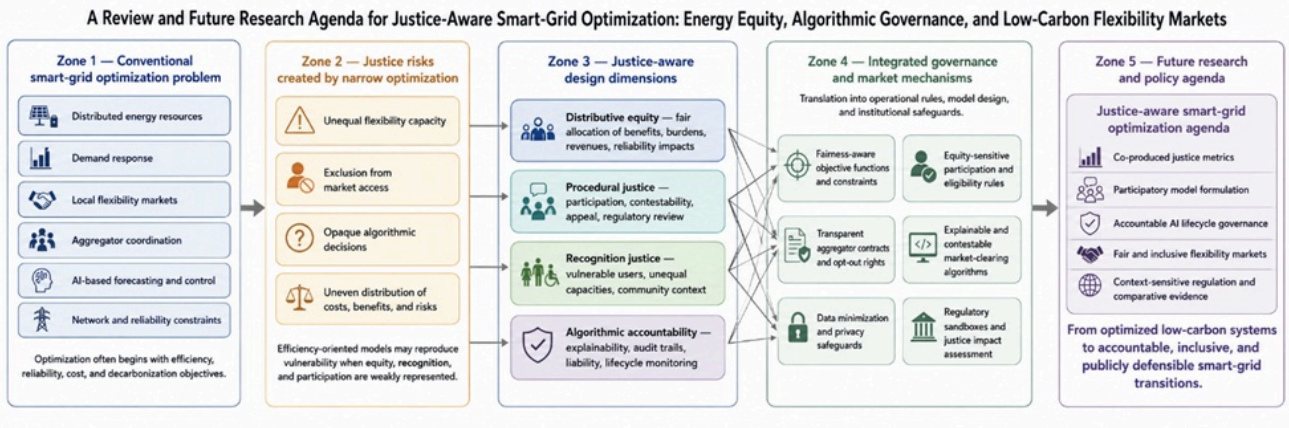


Figure 1. Justice-Aware Smart-Grid Optimization Pathway Linking Equity Principles, Algorithmic Governance, Flexibility Market Design, and Future Research Priorities

Table 3 sets out a structured research agenda linking gaps, proposed questions, methodological approaches, and expected outcomes for future justice-aware smart-grid optimization.

Table 3. Research Agenda for Advancing Justice-Aware Smart-Grid Optimization: Gaps, Questions, Methods, and Expected Contributions

Research gap	Proposed research question	Suggested approach	Expected outcome	Relevant justice contribution
Narrow equity metrics	How can optimization models represent distributive, procedural, and recognition justice together?	Combine fairness-constrained optimization with participatory metric design	Models that disclose and justify trade-offs	Broader justice operationalization
Weak governance integration	How should AI accountability be embedded in flexibility market rules?	Legal analysis, algorithm audits, and regulatory sandbox studies	Market designs with appeal, audit, and liability mechanisms	Stronger procedural fairness
Limited community participation	How can vulnerable communities shape flexibility programs before deployment?	Co-design workshops, deliberative methods, and community advisory boards	Context-specific participation safeguards	Improved recognition justice
Aggregator power	How do aggregator contracts affect prosumer	Comparative contract analysis and platform	Transparent rules for control, opt-out, and	Better agency and accountability

asymmetry	agency and consent?	governance assessment	compensation	
Distributional uncertainty	Who gains and who bears costs under different local market-clearing rules?	Scenario modeling linked to household vulnerability profiles	Equity-sensitive market evaluation tools	Fairer benefit and burden allocation
Fragmented regulation	What regulatory institutions are needed for AI-driven energy markets?	Cross-country policy comparison and institutional design research	Governance frameworks tailored to smart grids	Energy-specific algorithmic oversight

Policy Implications

Recommendations for regulators

Regulators should require that smart-grid optimization and flexibility market platforms undergo justice-oriented assessment before deployment. This assessment should include distributional analysis, explainability requirements, appeal procedures, and scrutiny of how vulnerable users are represented in data and models. El-Haber, Burnett, Halford, Stamp, De Silva, Manic, and Jennings support a lifecycle approach to AI ethics, which implies that regulatory approval should not end at initial deployment [14]. Regulators should therefore mandate continuous monitoring and revision when algorithmic systems produce unequal or poorly justified outcomes.

Market design principles

Market design should be guided by principles of inclusive access, proportional compensation, transparency, consent, and protection against unfair risk shifting. Local electricity market reviews show that mechanisms, solution concepts, and algorithmic techniques determine how welfare and participation opportunities are distributed [18]. Fair flexibility market design further demonstrates that equity considerations can be embedded into market mechanisms rather than added after efficiency has already been maximized [19]. Policymakers should therefore treat fairness constraints, consumer safeguards, and aggregator accountability as core market-design requirements.

International and contextual considerations

Justice-aware smart-grid policy must be context-sensitive because vulnerability, infrastructure capacity, regulatory authority, and digital access vary across places. Kumar’s work cautions against universal models of technical smartness, especially in settings where institutional and social conditions differ from the assumptions of advanced smart-grid markets [21]. Delina and Tung similarly show that vulnerable communities require specific attention in AI-assisted energy transitions, rather than being folded into generic innovation narratives [16]. International policy learning should therefore focus less on copying market templates and more on adapting justice principles to local social, technical, and regulatory realities.

Conclusion

Justice-aware smart-grid optimization is an emerging interdisciplinary agenda rather than a settled technical field. This review has argued that fairness, equity, and justice must be embedded in the design of optimization models, data practices, market rules, and governance institutions. The central challenge is not only to make algorithms more accurate or efficient, but to make smart-grid decision-making more accountable, inclusive, and socially legitimate.

The review shows that energy equity concepts provide essential guidance for evaluating distribution, participation, and recognition in smart-grid systems. However, these concepts can lose critical force when they are reduced to narrow

indicators or treated as secondary constraints. A justice-aware approach requires reflexive modeling choices, transparent assumptions, and meaningful engagement with the communities affected by automated grid decisions.

The future research agenda proposed here calls for stronger integration between optimization research, energy justice theory, AI governance, and flexibility market design. It emphasizes co-produced justice metrics, contestable algorithms, accountable aggregators, regulatory experimentation, and comparative research across different social and institutional contexts. These directions are intended to move the field from abstract commitments to operational, governable, and publicly defensible smart-grid systems.

Ultimately, low-carbon energy transitions will not be just simply because they are digital, decentralized, or optimized. They will become more just only if researchers, policymakers, regulators, industry actors, and communities actively shape smart-grid optimization around equity and democratic accountability. Justice-aware smart-grid optimization should therefore be understood as a shared socio-technical responsibility and a necessary condition for legitimate low-carbon transformation.

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