

Modelling energy justice

Reconceptualizing the modelling process to include procedural and recognition justice

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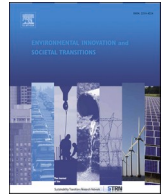
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Modelling energy justice: Reconceptualizing the modelling process to include procedural and recognition justice

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ABSTRACT

Interest in linking energy models with energy justice is growing, with a rising number of studies explicitly addressing the three tenets of justice – distributive, procedural, and recognition – and reviews mapping this field. Yet procedural and recognition justice have been treated in limited ways, leaving it unclear how models can meaningfully engage with them. This paper addresses this gap through a structured review of 63 peer-reviewed studies that develop or use models to support local and regional energy transition decisions while incorporating justice considerations. We find that procedural justice is primarily operationalized as stakeholder participation, with less efforts made to explicitly address other principles such as transparency, inclusivity, accountability and to include non-participatory ways of including stakeholder input. Recognition justice is either omitted or conflated with procedural principles, whereas energy justice literature defines it in systemic terms that extend beyond the mere acknowledgement of stakeholder groups. We argue that early-stage decisions such as funding, research design, and stakeholder selection significantly influence whose values are represented in models, whose knowledge is excluded, and which outcomes are prioritized. These influences, despite their justice implications, are rarely acknowledged, with existing efforts biased toward implementations of justice within model logic. We propose expanding the scope of modelling to include these early-stage influences and outline four recommendations for modellers: broaden justice conceptualizations beyond model logic; evaluate early-stage justice implications; adopt reflexive practices; and leverage multi-modelling approaches to capture the multi-dimensionality of energy justice.

1. Introduction

Local and regional governments face growing challenges in planning the energy transition. They must reduce CO₂ emissions to meet national climate targets while simultaneously responding to local priorities, addressing social concerns, and ensuring that the transition is fair and just for all segments of society. This is no simple task: energy transitions are inherently political and value-laden, involving diverse stakeholders with competing interests and unequal resources (Haas et al., 2023). Energy justice is

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multi-interpretable, with stakeholders holding different views of what constitutes a “just” transition (Taebi et al., 2020). Combined with the long timelines of implementation and impacts of energy transition decisions, the process is characterized by deep uncertainty and can be classified as a wicked problem (Cuppen et al., 2021; Rittel and Webber, 1973).

Computational models are increasingly used to support energy transition decision-making. Traditionally, these models have focused on the techno-economic dimensions of energy systems such as cost-optimality and energy efficiency, providing valuable quantitative insights (Horschig and Thrän, 2017). However, it has been argued that their suitability for engaging with the social dimensions of the transition such as justice and fairness remains limited (Chang et al., 2021). These models, despite ostensibly being technical tools, embed implicit normative choices (e.g., cost minimization) and risk reinforcing existing power imbalances if values such as justice and fairness are not made explicit (Li et al., 2016). Without deliberate attention to justice, seemingly objective modelling outcomes can risk legitimizing unfair outcomes for marginalized groups or for the environment.

There is rich ongoing debate over whether and how computational models should incorporate normative concerns like justice (Li et al., 2016; Süsser et al., 2021). Some scholars question whether abstract, qualitative, and contested concepts such as justice can or should be embedded in quantitative models (Pfenninger et al., 2014; Sovacool et al., 2015). There is however a growing consensus that interdisciplinary efforts are needed to bring energy justice and modelling literature into productive dialogue (Li et al., 2016; Riva-deneira and Carton, 2022; Sonja and Harald, 2018; Süsser et al., 2021). This is evident in the emergence of studies aiming to represent justice in energy models, and with recent reviews attempting to map this emerging field (Lonergan et al., 2023; Vågerö and Zeyringer, 2023).

Energy justice has been conceptualized in several ways. Some frameworks focus on core tenets – distributive, procedural, and recognition justice (McCauley et al., 2014) – while others focus on normative principles such as affordability, transparency, due process, and intergenerational equity (Jenkins et al., 2017; Sovacool et al., 2017). This paper adopts the three-tenets framework, as it is most frequently used in both theoretical and modelling studies (Vågerö and Zeyringer, 2023; Van Uffelen et al., 2024). Distributive justice relates to the fair allocation of costs, benefits, and risks; procedural justice, to fair and inclusive decision-making processes; and recognition justice, to the acknowledgement of diverse identities, values, and needs, particularly of non-dominant and marginalized groups (Williams and Doyon, 2019).

Existing reviews focus on modelling efforts that study distributive justice, typically using optimization models (Lonergan et al., 2023; Vågerö and Zeyringer, 2023). These efforts usually represent justice through metrics built into model logic, such as income-based equity indicators or spatial cost distribution measures. By “model logic,” we mean aspects related to the internal structure and functioning of the model, including its algorithms, equations, and the definition of input and output parameters. While such operationalizations remain valuable inputs for decision-making, they only capture a subset of energy justice considerations, with procedural and recognition dimensions of justice remaining underexplored in modelling literature, even as participatory and stakeholder-informed modelling approaches become more widespread (McGookin et al., 2022; Vågerö and Zeyringer, 2023). Procedural and recognition aspects of justice such as transparency, information asymmetry, power dynamics in decision spaces or the (ex-) inclusion of marginalized knowledge systems are not well-addressed in modelling contexts. As such, we argue there is a lack of a nuanced understanding of how procedural and recognition justice relate to energy models, and how these tenets might be meaningfully addressed by models. We therefore frame our research question as follows:

How do current energy models address distributive, procedural, and recognition justice, and what changes are needed to enhance their ability to support justice-oriented decision-making?

We respond to this question through a structured review of $N = 63$ peer-reviewed modelling studies. First, we revisit studies previously identified by other reviewers as addressing procedural or recognition justice, critically reassessing the basis for these classifications using a detailed coding framework derived from energy justice literature. Second, we broaden the scope beyond optimization models to include a wider range of modelling approaches, such as agent-based, system dynamics, simulation, and statistical models, using systematic literature search using Scopus and snowball sampling. This broader perspective allows us to analyze how different modelling approaches engage with justice and where key limitations or opportunities lie.

The paper is structured as follows: Section 2 provides an overview of the theoretical foundations of energy justice, outlining the three tenets and key challenges in linking them to energy models. Section 3 describes the methodology used to identify, review and analyse the 63 modelling studies. Section 4 presents the findings, detailing how distributive, procedural, and recognition justice are currently operationalized in models, followed by Section 5 that offers a discussion of key insights, building up to concrete recommendations for modellers and model users working with energy justice considerations.

2. Theory

2.1. Energy justice as procedural, distributive and recognition

The three tenets of energy justice: distributive, procedural, and recognition, serve as broad umbrella terms that encompass diverse justice concerns in the energy transition. These tenets serve as useful analytical and conceptual tools and offer a shared vocabulary for facilitating discussion on energy justice (Sovacool and Dworkin, 2015). While each tenet has a general definition, they are interpreted

normatively in different contexts (Van Uffelen et al., 2024).

Distributive justice is broadly understood as the distribution of "goods" (resources) and "bads" (harms and risks) (Williams and Doyon, 2019). Various normative principles underpin what constitutes a just distribution. Utilitarianism prioritizes the greatest good for the greatest number (Myerson, 1981). Egalitarianism considers a distribution unjust if some are left worse off than others (Rawls, 1971). Sufficiencyarianism holds that justice requires everyone to have enough resources (Miller, 2021). Prioritarianism gives priority to improving the welfare of the least advantaged (Adler and Holtug, 2019). In practice, these frameworks often translate into concerns over affordability, availability, and accessibility of clean energy (Williams and Doyon, 2019). In addition to distribution across societal groups, distributive justice concerns also span spatial and temporal dimensions such as regional equity and intergenerational justice (Williams and Doyon, 2019; Sasse and Trutnevyte, 2019) group distributive justice considerations across three dimensions: societal, spatial, and temporal.

Procedural justice concerns the fairness of decision-making processes, including who is involved, how decisions are made, and whether the process is transparent, accountable, and inclusive (Jenkins et al., 2016). Normative theories vary: the "all-affected principle" holds that justice entails giving voice to those impacted by decisions (Miller, 2021), while others focus on process quality, advocating for transparency, information access, and feedback mechanisms (Sovacool et al., 2017). Still others call for cultural tailoring and incorporation of local or indigenous knowledge systems (Van Uffelen et al., 2024). These frameworks show that procedural justice is more than just stakeholder engagement; it is also about their meaningful involvement and inclusive design of participatory processes.

Recognition justice focuses on whose identities, experiences, and knowledge systems are acknowledged and respected in decision-making (Jenkins et al., 2016). Two influential approaches include: Fraser's participatory parity principle, which sees misrecognition as an injustice as it can limit people from participating equally as their peers in social life (Fraser, 2023); and Honneth's self-realization principle, whereby recognition justice is through individuals' undistorted sense of self-worth and social esteem (Honneth (1996), van Uffelen (2022) proposes an integrative understanding of these two perspectives—justice as adequate recognition of all actors through love (social arrangements), law (institutional rights and duties), and status order (their needs, identities, cultural perspectives and knowledge). These views suggest recognition is not simply about inclusion but about addressing deeper structural and cultural exclusions.

While energy justice theory provides a rich conceptual foundation, integrating these tenets into computational energy models presents several challenges. Models prioritize formalization and quantification, ideas that align more easily with distributive justice (Lonergan et al., 2023). Procedural and recognition justice, which are processual and context-specific, can be relatively harder to represent through model logic. This can risk an over-reliance on measurable proxies such as equity indicators or stakeholder participation. While useful, these proxies risk oversimplifying the tenets they intend to represent. These limitations highlight a critical issue: efforts to incorporate justice in modelling tend to fit justice into the constraints of a model, rather than adapting the modelling approach to better reflect justice principles.

2.2. Gaps in existing reviews of justice in energy models

Recent reviews by Vågerö and Zeyringer (2023) and Lonergan et al. (2023) explore how energy models have incorporated justice. Both reviews focus on optimization approaches. (Vågerö and Zeyringer (2023) examine how the three tenets appear in model assumptions, structures, and outputs (building on the framework by Krumm et al. (2022)). Their conception of procedural justice is however limited to presence of participation and does not address principles such as transparency, inclusivity or responsibility. They do not include recognition justice in their review, due to lack of studies in their sample that address this tenet, thereby lacking nuances in exploring operationalizations of both procedural and recognition dimensions in models. Lonergan et al. (2023) identify eight energy justice discourses that the reviewed studies address, namely: spatial justice, job creation, energy access, health and disability, social marginalization, energy poverty, place identity and gender. They highlight that while models are particularly effective in representing concerns of distributive justice, they are currently not aligned with demands of practical policymaking, with their treatment of procedural or recognition justice considerations remaining limited. With over 89 % of their sampled studies focusing on distributive justice, (Vågerö and Zeyringer, 2023) consequently reflect that there is a need for comparative modelling studies to identify opportunities and perspectives that different modelling approaches may offer when it comes to addressing other aspects of justice.

Reviews of how other modelling approaches address social dimensions of the energy transition exist. For example, Dall-Orsoletta et al. (2022) review system dynamics models, (McGookin et al., 2021) review participatory modelling studies, and Krumm et al. (2022) analyse models used in EU Horizon projects. These studies examine how models integrate social aspects, but not specifically through a justice lens. As such, we lack an overview of how all three justice tenets, especially procedural and recognition justice, are addressed by different modelling approaches and what opportunities lie ahead for better approaching justice considerations through models.

3. Methodology

To understand how procedural, recognition and distributive justice tenets are incorporated in models, we conduct a review of energy modelling studies. This review includes papers published in academic peer-reviewed journals reporting on (the application of) an energy model(s). The papers were sampled in two ways: 1) through five review papers that did a similar review of models and justice-related aspects, and 2) through a keyword search on Scopus.

As for the first sampling strategy, we include models from the following five review papers: a) Vågerö and Zeyringer (2023) and Lonergan et al. (2023) who focus on inclusion of justice in optimization models; b) Dall-Orsoletta et al. (2022) who review integration

of social aspects in System Dynamics models; c) [McGookin et al. \(2021\)](#) who review participatory modelling approaches and d) [Krumm et al. \(2022\)](#) who analyse inclusion of social aspects in Energy System Optimization Models (ESOMs), Energy System Simulation Models (ESSMs), Agent-based models (ABMs) and System Dynamics (SD) models used in EU-HORIZON projects.

For our keyword search, the following terms were searched across titles, abstracts, and keywords: “energy transition” AND (“tenet” OR “justice” OR “fair” OR “fairness” OR “inequ*” OR “equit*”) AND (“procedur*” OR “distributi*” OR “recogni*”) AND “model”. We limited the results to peer-reviewed English-language journal articles published between 2009 and 2024 and applied the following inclusion criteria: a) they concern decision-making in the energy transition at the local and regional level, b) they include a computational model that serve as one of the decision-support tools, and c) engages implicitly or explicitly with justice considerations in relation to modelling. We excluded global or national-scale studies (e.g., Integrated Assessment Models), as our focus is on models that can address issues at the local and regional (sub-national) levels of governance. This process ([Fig. 1](#) provides a visual summary) resulted in 63 papers included for analysis

We developed a two-stage coding process to assess how each paper engaged with energy justice. In the first stage - descriptive coding - each paper was analyzed using a set of general descriptors. These included the case study location (if applicable), the name of the model and the modelling approach used (e.g., optimization, system dynamics), and the type of energy transition decision the model was designed to support. We also recorded whether the modelling process involved stakeholder engagement, and if so, at what stages. Additionally, we noted how stakeholder input was incorporated into the modelling process, and how justice considerations were operationalized either through model structure or a technique such as multi-criteria decision analysis (MCDA), Gini coefficients, or scenario constraints. In defining what constitutes a “modelling process”, we adopt a wider scope than previous studies encompassing the full sequence of activities involved in developing and using a model ([Cuppen et al., 2021](#); [DeCarolis et al., 2017](#); [McGookin et al., 2024](#)). This includes not only its technical development, consisting of phases such as model conceptualization, data collection, implementation, verification and validation, but also the broader decisions and practices that shape how it is chosen, created, used and interpreted, such as funding, the composition of the modelling team, and related organisational or contextual factors. We keep this broader scope, as we hypothesize that these decisions made at these stages can have justice implications, drawing from [Giang et al. \(2024\)](#).

The descriptors used in the review are summarized in [Table 1](#) below.

In the second stage - justice coding - we analysed how each paper operationalized the three tenets of energy justice using a detailed codebook derived from energy justice literature (see [Section 2](#)). Each paper was reviewed for explicit mentions of one or more of the tenets, for mentions identified by the review articles (in the case of review-sourced studies), and for implicit engagement with justice aspects based on the codes presented in [Table 2](#). This approach allowed us to assess whether and how justice considerations were embedded either within the model logic - for instance, through output metrics or decision variables- or within the modelling process, such as through participatory methods, design decisions, or efforts to ensure transparency. It is worth noting that recognition justice is the only tenet where explicit forms of injustice (i.e., misrecognition) were coded. Distributive and procedural justice on the other hand,

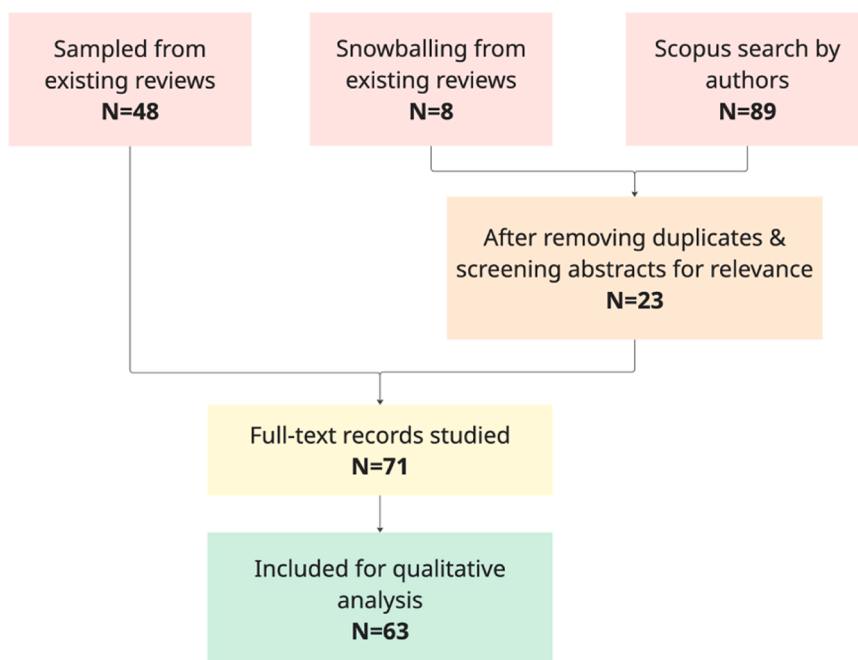


Fig. 1. Overview of sampling process for review.

Table 1

Descriptive coding frame used for each study.

Descriptor	Description	Example / Notes
Case location	Geographic scope of the study, if applicable	Region, municipality, city, neighborhood, or household
Model name	Name of the model used or developed in the study	TIMES, LEAP, custom-built models
Approach	Type of computational modelling approach used	Optimization, system dynamics, agent-based modelling, integrated energy system simulation, game theory, choice models
Decision supported	Type of decision the model is designed to inform	Technology choice, infrastructure planning, policy design, investment strategy
Technique	How justice considerations are embedded in the model or modelling process	Output metrics (e.g., Gini coefficient), model constraints, decision variables, scenario design, MCDA/MCA methods
Participatory?	Whether stakeholders are involved in the modelling process	Yes/No
Stakeholders	Types of stakeholders included in the process	Residents, NGOs, local governments, energy cooperatives, businesses
Stakeholder stage	Stage(s) in the modelling process where stakeholders contribute	Problem framing, model conceptualization, scenario design, result interpretation
Input use	How stakeholder contributions are translated into the model	Adjusting input parameters, validating assumptions, selecting outputs or scenarios
Iterative?	Whether and how stakeholder engagement occurs more than once	Yes: feedback loops, repeated workshops; No: one-time consultation

Table 2

Energy justice coding framework, based on energy justice literature (listed alphabetically) including [Fraser \(2023\)](#), [Honneth \(1996\)](#), [Jenkins et al. \(2016\)](#), [McCauley et al. \(2014\)](#), [Rawls \(1971\)](#), [Sovacool and Dworkin \(2015\)](#), [Sovacool et al. \(2017\)](#), [van Uffelen \(2022\)](#), [Walker \(2012\)](#), [Van Uffelen et al. \(2024\)](#), and [Williams and Doyon \(2019\)](#).

Energy justice tenet	Interpretation	Code assigned	Sub-code (if applicable)
Distributive Justice	Model outputs addressing distribution of costs, benefits, or burdens across social groups, space, time, or species	Distribution across society	Fair distribution of economic costs and benefits Fair distribution of non-economic costs and benefits
		Distribution across space	Regionally equitable distribution of costs and benefits Distribution of costs and benefits beyond the region of study (cosmopolitanism)
		Distribution across time	Intergenerational equity Compensation of past harms (restorative)
Procedural Justice	The modelling process involves stakeholders in providing input, evaluating outcomes, or shaping scenarios, through participatory processes. While their input shapes model logic, assumptions or structure, stakeholders are typically not involved directly in model development or use. Stakeholders and modellers jointly determine the model's structure, parameters, and assumptions, representing a deeper level of engagement where stakeholders have greater agency in defining how the real-world system is represented and tested. Stakeholder preferences and values are directly incorporated into the model logic, objectives, or constraints without their direct involvement. Stakeholders' preferences are inferred from prior experience, earlier studies, or literature; these in turn shape the model.	Distribution across species Stakeholder engagement in modelling process (participatory)	Inter-species justice
		Co-constructing the model together with stakeholders	
Recognition Justice	Participatory processes are designed to meaningfully include underrepresented voices and community perspectives, or conversely, may fail to do so, reflecting (mis) recognition in enabling participative parity. Models reflect structural inequality, heterogeneity, or marginalized experiences through their assumptions, structures, or outputs. This includes when social diversity is represented as well as where exclusion is reproduced through systems, assumptions and structures. Communities define their own energy needs and aspirations, which shape the model structure and outputs.	Including stakeholder preferences and values into model logic (non-participatory)	
		Ensuring transparent and inclusive models/modelling processes	
		(Mis)recognition in modelling process and participatory parity	
		(Mis)recognition in model	
		Self-realization principle	

are coded positively (for e.g., fairness of distribution, inclusivity and transparency of procedures) rather than for their absence (i.e., unfairness or exclusion). This asymmetry is reflective of how modelling studies approach these tenets – with the intention to explore performance on objectives or metrics of justice, rather than for diagnosing harms or exclusion. However, this is not entirely the case for distributive justice; although it is coded positively (e.g., “fair distribution across society”), the metrics used, such as the Gini coefficient, allow outcomes to be evaluated in terms of how equitable they are. Thus, less fair distributions are identified as inequitable outcomes, enabling the detection of distributive injustices even within a positively framed coding scheme. Having clarified this distinction, we describe these codes in the following sections that are dedicated to discussing each of the three tenets.

An overview of all papers, and models presented in those papers, included in the review can be found in the Supplementary Material.

4. How models currently operationalize energy justice

In this section, we provide an overview of how different modelling approaches operationalize distributive, procedural and recognition justice. Among the three tenets, distributive justice was the most extensively addressed, especially in studies employing optimization-based modelling approaches. Accordingly, we structure this section by first analysing how distributive justice is operationalized in optimization models, followed by a discussion of non-optimization models such as agent-based, econometric, or game-theoretic approaches. We apply this division uniquely to distributive justice because the modelling approach significantly shaped how fairness was conceptualized and embedded within model logic and outputs. In contrast, the treatment of procedural and recognition justice was less dependent on model type and more influenced by broader modelling design and process-level decisions. Therefore, we do not apply a similar subdivision by modelling approach in [Sections 4.2 and 4.3](#) ([Table 3](#)).

The following sections delve deeper into how these interpretations of the three justice tenets are addressed by different modelling approaches.

Table 3

Overview of the different justice considerations addressed by different modelling approaches. The sum exceeds $N = 63$ as some studies address multiple considerations.

Modelling approach	Tenet	Number of studies ($n=$)
Optimization	<i>Distributive</i> : Fair distribution of economic costs and benefits	14
	<i>Distributive</i> : Fair distribution of non-economic costs and benefits	7
	<i>Distributive</i> : Regionally equitable distribution of costs and benefits	17
	<i>Procedural</i> : Stakeholder engagement in modelling process	5
	<i>Procedural</i> : Ensuring transparent and inclusive models/modelling processes	3
	<i>Procedural</i> : Including stakeholder preferences and values into model logic (non-participatory)	10
	<i>Recognition</i> : (Mis)recognition in modelling process and participatory parity	1
	<i>Distributive</i> : Intergenerational/inter-species distribution	1
Simulation & Hybrid	<i>Distributive</i> : Fair distribution of economic costs and benefits	1
	<i>Distributive</i> : Regionally equitable distribution of costs and benefits	2
	<i>Procedural</i> : Stakeholder engagement in modelling process	7
	<i>Procedural</i> : Ensuring transparent and inclusive models/modelling processes	6
	<i>Recognition</i> : (Mis)recognition in modelling process and participatory parity	2
	<i>Recognition</i> : Self-realization	2
	<i>Recognition</i> : (Mis)recognition in models	2
System Dynamics	<i>Distributive</i> : Fair distribution of economic costs and benefits	1
	<i>Distributive</i> : Fair distribution of non-economic costs and benefits	1
	<i>Distributive</i> : Regionally equitable distribution of costs and benefits	1
	<i>Procedural</i> : Stakeholder engagement in modelling process	2
	<i>Procedural</i> : Co-construction of models	1
	<i>Procedural</i> : Ensuring transparent and inclusive models/modelling processes	1
	<i>Procedural</i> : Including stakeholder preferences and values into model logic (non-participatory)	1
	<i>Recognition</i> : (Mis)recognition in models	1
Agent-Based Models (ABM)	<i>Distributive</i> : Fair distribution of economic costs and benefits	3
	<i>Distributive</i> : Fair distribution of non-economic costs and benefits	5
	<i>Distributive</i> : Regionally equitable distribution of costs and benefits	1
	<i>Recognition</i> : (Mis)recognition in models	1
Game Theory	<i>Distributive</i> : Fair distribution of economic costs and benefits	5
	<i>Distributive</i> : Fair distribution of non-economic costs and benefits	3
Choice Modelling	<i>Distributive</i> : Fair distribution of economic costs and benefits	2
	<i>Distributive</i> : Regionally equitable distribution of costs and benefits	2
	<i>Procedural</i> : Stakeholder engagement in modelling process	3
	<i>Procedural</i> : Including stakeholder preferences and values into model logic (non-participatory)	1
	<i>Distributive</i> : Intergenerational/inter-species distribution	1
	<i>Distributive</i> : Fair distribution of economic costs and benefits	1
	<i>Distributive</i> : Fair distribution of non-economic costs and benefits	3
Statistical Models	<i>Distributive</i> : Regionally equitable distribution of costs and benefits	2
	<i>Procedural</i> : Stakeholder engagement in modeling process	1
	<i>Procedural</i> : Ensuring transparent and inclusive models/modelling processes	1
	<i>Recognition</i> : (Mis)recognition in models	1

4.1. Distributive justice

Distributive justice is typically operationalized through model outputs, most often as the distribution of costs, benefits, or burdens across space or social groups. These outputs are usually quantified using indicators like income, location, access, or externalities such as air pollution. We structure this analysis by modelling approach – optimization and non-optimization – each addressing distributional concerns in distinct ways.

4.1.1. Optimization approaches

Vågerö and Zeyringer (2023) and Lonergan et al. (2023) already provide detailed accounts of how optimization models address distributive justice. Because our sampling substantially overlaps with theirs, we keep this subsection brief and avoid re-describing how studies operationalize distributive justice aspects. Below we briefly summarize insights from our review, distinguishing optimization models that address distributive fairness across dimensions of society and space, and highlighting elements most relevant to our sample. A tabular summary of results can be found in Table 4.

Across society: We observe a broad division between studies focusing on economic costs and benefits across society ($n = 9$) and those addressing non-economic costs and benefits ($n = 7$). On the economic side, models examine equitable electricity pricing and cost burdens; for e.g., affordability-based tariffs and income-disaggregated impacts (Li et al., 2016; Menghwani et al., 2020; Fell et al., 2020). In decentralized systems, many studies pair optimization models with game-theory methods to explore allocation of profits/costs based on explicit fairness principles. For e.g., marginal contribution/Shapley–Shubik (Wu et al., 2017; Fioriti et al., 2021), generalized Nash bargaining reflecting market power (Kim et al., 2019), or equalized profit-growth rates across microgrids (Jafari et al., 2020). Non-economic dimensions include employment effects (Patrizio et al., 2018), thermal comfort and fair load reduction (Bhattacharya et al., 2019; Ferro et al., 2020; Funde et al., 2018), demographic disparities in pollution exposure (Goforth and Nock, 2022), fairness in PV curtailment (Gebbran et al., 2021), and the use of public acceptance weights or cost penalties to reflect social opposition in constraints/scenarios (Koecklin et al., 2021; Bolwig et al., 2020). We did not identify optimization studies in our sample that operationalize intergenerational or compensatory justice, so the temporal dimension is not covered here.

Across space: Costs are conceptualized via regional electricity prices (e.g., Menghwani et al. (2020), Bolwig et al. (2020)), the allocation of RE capacity (wind/solar) across regions (Sasse and Trutnevyte, 2019; Wang et al., 2019), visual intrusion using “scenicness” constraints (Price et al., 2022; Weinand et al., 2021), and particulate-matter or other externalities (e.g., Sasse and Trutnevyte (2020), Grimsrud et al. (2021)). Benefits are often framed as energy access and the reduction of regional access gaps (Nock et al., 2020; Trotter et al., 2019). As also noted by Vågerö and Zeyringer (2023), techniques range from equity metrics embedded in objectives/constraints to scenario-based exploration and near-optimal searches. For evaluating energy system configurations from a justice perspective, equity metrics – most commonly the Lorenz curve/Gini coefficient – are used to quantify the (in)equality of distributions. These metrics assess, for example, spatial equity in RE siting across regions (Sasse and Trutnevyte, 2019; Wang et al., 2019), disparities in regional consumption/access (Nock et al., 2020), and other spatially resolved burdens/benefits. Finally, Modelling to Generate Alternatives (MGA) is a method frequently used with optimization approaches, to explore near-optimal solutions that result in spatial configurations which are not cost-optimal, but perform better on other metrics such as spatial equity, social acceptability or align better with metrics that are important to stakeholders (Sasse and Trutnevyte, 2020; Neumann and Brown, 2021; Lombardi et al., 2020).

4.1.2. Non-optimization approaches

Across society: In non-optimization approaches, distributive justice across society is explored through game theory, econometrics, agent-based modelling or choice modelling methods. Similar to optimization approaches, we observe a distinction between studies focusing on economic costs and benefits across society ($n = 5$) and those addressing non-economic costs and benefits ($n = 9$). Economic costs and benefits are examined through approaches that assess fair allocation of profits, revenues, or costs among actors in the energy system. For example, Chen et al. (2020) apply cooperative and non-cooperative game theory to explore fair allocation of profits among prosumers in community energy systems, using methods such as the Shapley value and Nash bargaining. Baharlouei et al. (2013) use Shapley value to conceptualize fair cost-sharing mechanism by allocating demand response costs proportionally to users’ contributions, so as to reflect individual roles in achieving collective efficiency. Non-economic benefits are frequently conceptualized as access (or lack thereof) to clean energy. Ding et al. (2023) and Rahut et al. (2024) use statistical models to assess how socio-demographic indicators like race, caste, gender, and income correlate with disparities in solar adoption or access to clean energy services. Agent-based models are used to explore technology adoption under different policy schemes. Heymann et al. (2019) apply Theil’s T-index to track inequities in solar PV and electric vehicle uptake under different incentive schemes. Their findings reveal how specific policy instruments can exacerbate or mitigate disparities between income or demographic groups. Rai and Robinson (2015), Sundaram et al. (2024), and Brugger and Henry (2019) develop ABMs to model the socio-demographic impacts of policy interventions in solar PV adoption, showing how social networks structures that households are embedded in can influence equity outcomes of policy interventions, calling for justice-aware design of incentive schemes.

Across Space: Simulation, choice modelling, and agent-based approaches offer different ways of addressing spatial justice, often focusing on perceived fairness, policy responsiveness, and technology adoption across regions. Henni et al. (2023) employ a hybrid simulation-optimization model to compare equity trade-offs between centralized and decentralized energy infrastructure configurations. While total system costs are still considered, the central concern is how different planning approaches affect the spatial distribution of burdens and benefits – especially in terms of perceived fairness and local acceptance. The underlying assumption being that, a more regionally balanced siting of generation infrastructure may enhance perceived fairness and social acceptance of the transition.

Table 4

Overview of optimization models approach distributive justice considerations.

Distributive Justice	Focus	Approach	Examples of studies
Across society: Economic costs and benefits	Designing equitable electricity pricing	Applying equality (uniform pricing) and equity (affordability-based) principles	(Menghwani et al., 2020)
	Analyzing energy costs across social groups	Assigning socio-economic profiles to households to estimate differentiated burdens	(Li et al., 2016; Fell et al., 2020; Bolwig et al., 2020)
	Equitable profit distribution in microgrids	Game theory and bargaining solutions based on marginal contribution, market power, or equalized profit growth	(Wu et al., 2017; Fioriti et al., 2021; Kim et al., 2019; Jafari et al., 2020)
Across society: Non-economic costs and benefits	Employment impacts of energy policy	Linking optimization outputs to labor market models or employment data	(Patrizio et al., 2018)
	Guaranteeing thermal comfort under constrained supply	Demand response algorithms and fairness-constrained optimization	(Bhattacharya et al., 2019)
	Fair load reduction or energy sharing	Including fairness parameters to ensure equitable energy distribution or curtailment	(Ferro et al., 2020; Funde et al., 2018; Gebbran et al., 2021)
Across space	Disparities in pollution exposure	Linking emissions from energy scenarios to demographic vulnerability data	(Goforth and Nock, 2022)
	Social acceptance in siting and infrastructure planning	Modelling willingness-to-accept/pay and including regional acceptance weights	(Koecklin et al., 2021; Bolwig et al., 2020)
	Visual intrusion based on public preferences	Using crowd-sourced scenicness data as constraint in siting optimization	(Price et al., 2022; Weinand et al., 2021)
	Fairness in spatial allocation of RE infrastructure	Applying Gini coefficient to per capita/demand-based allocations	(Sasse and Trutnevyte, 2019; Wang et al., 2019)
	Regional fairness in energy access or burden	Incorporating equity indicators and environmental costs in objectives or constraints	(Koecklin et al., 2021; Grimsrud et al., 2021; Nock et al., 2020; Trotter et al., 2019)
	Exploring near-optimal spatially fair scenarios	Modelling to Generate Alternatives (MGA) is used to reveal distributional trade-offs with non-cost based metrics	(Sasse and Trutnevyte, 2020; Neumann and Brown, 2021; Lombardi et al., 2020)

Perceptions of fairness are explored through choice experiments which involve direct citizen or resident input. Drechsler et al. (2017) present citizens with different spatial configurations of renewable energy deployment that are generated by optimization models, which are based on egalitarian or utilitarian fairness principles. The Gini coefficient is used as the measure of equity in these spatial allocations. Citizens' choices are then analysed to assess which trade-offs between cost-efficiency and regional fairness are considered most acceptable. Schmidt-Scheele et al. (2022) go further by incorporating broader justice concerns within their choice experiment such as intergenerational equity and distribution of burdens across different societal groups. Their findings highlight the

Table 5

Overview of non-optimization approaches address distributive justice considerations.

Distributive Justice	Focus	Approach	Examples of studies
Across Society: fair distribution of economic costs and benefits	Fair pricing in demand response algorithms	Cooperative game theory (e.g., Shapley value) to allocate charges based on contribution	(Baharlouei et al., 2013)
	Profit allocation in community energy trading	Shapley value, Nash bargaining, Nucleolus, Stackelberg games for equitable revenue sharing	(Wu et al., 2017; Fioriti et al., 2021; Kim et al., 2019; Chen et al., 2020)
Across Society: fair distribution of non-economic costs and benefits	Socio-economic disparities in clean energy access & costs of the energy transition	Econometric models are used to examine how disparities in access link to socio-demographics.	(Ding et al., 2023; Rahut et al., 2024)
	Distributional impacts of RE adoption programs	Choice-models that help analyze citizens preferences for different burden sharing rules Agent-based models to simulate technology adoption and evaluate socio-demographic equity using metrics like Theil's T-index	(Kanberger and Ziegler, 2023; Groh and Ziegler, 2018) (Heymann et al., 2019; Rai and Robinson, 2015; Sundaram et al., 2024; Brugger and Henry, 2019)
	Inter-species justice: Distribution of impacts to non-human subjects	Choice-models that help analyze citizens preferences for justice considerations	(Schmidt-Scheele et al., 2022)
Across Time Across space	Intergenerational justice		
	Simulating spatial equity vs. cost trade-offs	Hybrid optimization-simulation model to evaluate centralized vs. decentralized infrastructure	(Henni et al., 2023)
	Capturing fairness perceptions of spatial allocations	Choice experiments evaluating citizen preferences for allocations generated by energy models based on fairness principles	(Drechsler et al., 2017)
	Capturing citizen preferences on broader justice dimensions	Discrete choice experiment (Random Parameter Logit) combined with focus groups to explore intergenerational and burden-sharing justice	(Schmidt-Scheele et al., 2022)

limitations of conventional energy models in capturing the full range of justice considerations valued by the public. Their study stands out as the only one in the review to explicitly address distribution across time, emphasizing trade-offs between present and future generations.

Agent-based models in this category are used to simulate spatially explicit adoption dynamics in response to policy interventions. Heymann et al. (2019), Rai and Robinson (2015), and Sundaram et al. (2024) model how different demographic groups respond to financial incentives for rooftop solar and electric vehicle adoption. These ABMs can help explore how some interventions may lead to uneven adoption across regions, potentially reinforcing or mitigating existing spatial and/or social inequalities in access to energy technologies.

A tabular summary of results can be found in Table 5.

4.2. Procedural justice

As outlined in Section 2.1, energy justice literature defines procedural justice as concerning fairness of energy transition decision-making processes, ensuring they are inclusive, transparent, accountable, and follow due process. It involves providing equal access to information, representing diverse voices, and enabling the meaningful participation of all affected stakeholders: not only dominant actors but also marginalized or under-represented groups. In the context of modelling, procedural justice can be addressed in both

Table 6

Overview of how models address procedural justice considerations.

Procedural Justice	Focus	Approach	Examples of studies
Transparent and inclusive models/modelling processes	Use of open data, open-source models	Models and documentation are open access.	(McKenna et al., 2018)
	Models are made accessible and interactive for use in participatory exercises.	Models are simplified (e.g., Excel, dashboards) or downscaled for engagement in workshops and decision-making	(McKenna et al., 2018; Schinko et al., 2019; Blumberga et al., 2022; Flacke and De Boer, 2017)
	Ensuring a diverse set of participants/perspectives are represented in the model/modelling process	Stakeholder engagement includes different groups and communities not just experts	(Blumberga et al., 2022; Sharma et al., 2020)
Stakeholder Engagement in modelling process	Collecting preferences through workshops, surveys, focus groups	Inputs are translated into MCDA/MCA frameworks within optimization, simulation, or power system models	(Heaslip and Fahy, 2018; Krzywoszynska et al., 2016; Bertsch and Fichtner, 2016; den Herder et al., 2017)
	Using MCDA to evaluate outcomes based on stakeholder preferences	Stakeholders assess and rank model outputs using predefined or stakeholder-defined criteria	(Simoes et al., 2019)
	Eliciting stakeholder knowledge of the system and uncertainties	Mapping techniques (e.g., PSM, Bayesian networks) are used and translated into simulation or system dynamics models	(Bernardo and D'Alessandro, 2019; Düspohl et al., 2012)
	Scenario workshops to create equity-oriented narratives	Qualitative scenarios developed by stakeholders are explored through optimization or simulation models	(Schinko et al., 2019; Fortes et al., 2015)
	Using MCA to include local priorities in scenario design	Preferences are captured as weighted criteria in simulation models	(Zelt et al., 2019)
	Understanding perceptions of fairness in model outcomes	Stakeholders evaluate RE spatial allocations or policy options via choice experiments integrated with modelling	(Drechsler et al., 2017; Kanberger and Ziegler, 2023; Groh and Ziegler, 2018)
Co-constructing the model together with stakeholders	Participatory modelling processes involving shared development of model structure	Participatory system dynamics modelling and scenario visioning jointly conducted with stakeholders	(Olabisi et al., 2010)
Including stakeholder preferences and values into model logic	Quantifying public acceptance through proxy indicators	Use of scenicness data to reflect visual concerns in model constraints	(Weinand et al., 2021)
	Quantifying acceptance/resistance as added system costs	Social resistance is modelled as cost penalties reflecting delays or risks	(Bolwig et al., 2020)
	Designing energy system narratives based on energy justice and simulating them in system dynamics models	Justice-based energy access scenarios are modelled and compared using system dynamics	(Gladkykh et al., 2021)
	Exploring socially acceptable spatial allocations of RE	Optimization models combined with MGA to generate scenarios minimizing land use, conflicts, or maximizing equity/self-sufficiency	(Lombardi et al., 2020; Neumann, 2021; Chen et al., 2022)
	Adding constraints reflecting public acceptability	Constraints on siting or capacity are based on stakeholder or regional preferences	(Koecklin et al., 2021; Fitiwi et al., 2020)
	Minimizing environmental or social externalities in the objective function	Cost functions include impacts such as infrastructure burden or social/environmental costs	(Grimsrud et al., 2021)

participatory and non-participatory ways. Participatory approaches include co-developing models with stakeholders or directly incorporating their inputs into model design and application through engagements such as workshops, focus groups, interviews or choice experiments. Non-participatory approaches occur when modelers or model users integrate their understanding of stakeholder preferences and values into the conceptualization, implementation, or interpretation of a model without stakeholders being directly involved. For example, stakeholder priorities may be inferred from secondary data, or literature, and then embedded into the model structure or scenarios. It can be argued that such practices still fall within the conceptualization of procedural justice because it reflects an effort to include stakeholder perspectives, ensuring decisions reflect their values and preferences, even if stakeholders are not directly present. While prior reviews (Vågerö and Zeyringer, 2023) have equated procedural justice in modelling with direct participation, our findings suggest otherwise. Out of 63 studies, we find 30 studies addressing some aspects of procedural justice and amongst them we identify an equal number of studies ($n = 15$) that operationalize procedural justice through participatory and non-participatory ways each. We therefore distinguish between these two pathways in our results. A tabular summary of results can be found in Table 6.

Modelling studies generally take one of the following approaches towards procedural justice: (1) ensuring transparent and inclusive models/modelling processes; (2) engaging stakeholders via participatory processes to gather their input at different stages in the modelling process; (3) co-constructing the entire model together with stakeholders; and (4) embedding stakeholder preferences/knowledge/values directly into the model logic without necessarily involving them in participatory exercises (non-participatory). We highlight and discuss some examples of each of these approaches below.

4.2.1. Transparent and inclusive models/modelling process

This approach reflects principles of transparency, accessibility, and inclusivity and is addressed in modelling contexts by either modifying the model for use in participatory settings or by adjusting the process around its use in such exercises. Transparency is addressed by using open-source models, open-access data, or detailed documentation that allows external scrutiny and replicability. Inclusivity is addressed by simplifying models or improving their accessibility by building interfaces to reduce cognitive barriers and by designing processes that actively involve underrepresented or marginalized voices. McKenna et al. (2018) address both these aspects in their study, with a focus on making their optimization models accessible to smaller communities by using open data and facilitated workshops. They emphasize that complex modelling tools are often inaccessible to non-experts, and their participatory development approach helps make technical decisions more legible and inclusive. Schinko et al. (2019) use a downscaled version of a larger simulation model *renpass*, which is a spreadsheet-based tool called *renpass-GIS*. This downscaled version is aimed at reducing complexity, runtime and improving understandability, so as to better align with users' needs when co-developing energy scenarios in participatory workshops. Blumberga et al. (2022) design a web-based System Dynamics interface aimed at lowering barrier of use for public engagement and to enable lay users to explore policy scenarios and their implications. Flacke and De Boer (2017) develop an interactive planning support tool called COLLAGE, which enables local stakeholders to explore trade-offs and consequences of spatial planning decisions, contributing to mutual learning and consensus-building. When it comes to inclusivity, Sharma et al. (2020) and Blumberga et al. (2022) document explicit efforts made to ensure the representation of diverse participant groups during the participatory process. Such decisions concerning research design, such as how the tool is built and who is defined as a stakeholder and is invited for participation, reflect motivations to include principles concerning procedural justice.

4.2.2. Stakeholder engagement in the modelling process

Stakeholder engagement is the most common way by which modelling studies approach procedural justice. The form of engagement varies between studies and ranges from surveys and interviews to focus groups and workshops, aimed at eliciting stakeholder input on energy scenarios, system understanding, or criteria for evaluating model outcomes or exploring trade-offs between different solutions. Stakeholder inputs gathered from participatory exercises are then translated into modelling structures, assumptions, or parameters by modellers.

Some studies use methods that are designed to systematically elicit and integrate stakeholder knowledge of system behavior and uncertainty into model development. We highlight two examples. Firstly, Bernardo & D'Alessandro (Bernardo and D'Alessandro, 2019) use participatory system mapping (PSM) in the early conceptualization phase to capture causal relationships and feedback loops that reflect local understanding of energy transitions. These maps are the basis for analytical System Dynamics models that are further developed by modellers. Second, Düspohl et al. (2012) use participatory Bayesian network modelling to integrate both system knowledge and stakeholder perceptions of uncertainty into their model.

The other common way to involve stakeholders and gather their narratives is through participatory scenario development and visioning in combination with hybrid optimization+simulation models. Who is involved as a stakeholder differs between studies, with most studies working together with policy makers and experts to co-develop socio-economic storylines that shape future energy scenarios (for example see Fortes et al. (2015) and Schinko et al. (2019)). Fewer studies work directly with communities, where the stakeholder group involves residents and laypersons. Some examples of community involvement are Heaslip and Fahy (2018) where they co-design energy transition scenarios with residents of the island of Krzywoszynska et al. (2016) who use maps, physical models, and images to engage residents in developing future energy scenarios, which are then later linked to energy system models. These approaches can be said to embed the procedural justice principle of community empowerment, as they enable communities to shape the futures that are imagined through these models.

Methods such as Multi-Criteria Decision Analysis (MCDA) and Multi-Criteria Assessment (MCA) are widely used in participatory modelling tools, especially in conjunction with optimization models, as they allow stakeholders define and weight the criteria used to evaluate scenarios. Bertsch and Fichtner (2016) integrate public concerns like noise, health risks, and aesthetics into grid expansion

planning. [den Herder et al. \(2017\)](#) gather stakeholder input on criteria such as biodiversity and employment to design bioenergy scenarios. [Simoes et al. \(2019\)](#) use MCDA to allow stakeholders to evaluate a city-level optimization model on dimensions like quality of life, indoor comfort, and local economic impact. [Zelt et al. \(2019\)](#) apply MCA to reflect local stakeholder priorities when assessing electricity futures using the *renpass-GIS* model, highlighting the socio-technical nature of transition planning.

Public perspectives on fairness are also captured through choice experiments. [Drechsler et al. \(2017\)](#) assess public preferences for spatial energy allocations based on fairness principles (e.g., egalitarianism vs. utilitarianism), and link those to model outputs. [Groh and Ziegler \(2018\)](#), and [Kanberger and Ziegler \(2023\)](#) use choice modelling to compare public preferences for burden-sharing rules such as polluter-pays or equal-pay approaches.

4.2.3. Co-construction of models

Although stakeholder participation is common, full co-construction of models – where stakeholders are also involved in defining technicalities of the model including model structure, parameter values and ranges, feedback mechanisms, and system boundaries – is not common. [Olabisi et al. \(2010\)](#) present a notable exception. Their participatory system dynamics approach involves stakeholders in collaboratively define system boundaries, causal relationships, and policy levers by using tools such as causal loop diagrams. This type of engagement allows for shared problem framing and procedural inclusion of stakeholders in how models are used to inform decisions. A few other studies adopt elements of this approach, though the translation of stakeholder input into quantitative models often remains the sole domain of the modeller. While we do not classify these as fully co-constructed, they merit mentioning within this category. For example, [Heaslip and Fahy \(2018\)](#) reflexive energy-planning workshops; [Bernardo and D'Alessandro \(2019\)](#) who use a Participatory System Mapping (PSM) approach to develop qualitative sub-models of energy sectors as the basis for quantitative system dynamics models; and [Düspohl et al. \(2012\)](#) whose Bayesian Network model is built entirely from stakeholder inputs gathered through multiple engagement methods, including interviews, focus groups, and workshops.

4.2.4. Embedding stakeholder preferences into model logic (non-participatory)

This category includes studies that incorporate stakeholder preferences or societal values into models through non-participatory means. Rather than being elicited directly through engagement processes, these values are derived from prior survey data, literature, or modellers' assumptions about what concerns matter to affected stakeholders. These preferences are then embedded into the model logic, typically through constraints, objective functions, or scenario design. While indirect, this form of inclusion still reflects aspects of procedural justice, as it involves considering stakeholder-relevant criteria when shaping model behaviour and outputs. Furthermore, it highlights that these modelling choices – such as what is treated as a cost or benefit, or which impacts are minimized – are not value-neutral. Through these choices, modellers determine what is being distributed, what is defined as a cost or benefit, to whom, and with what implications. As such, they mark key junctures where stakeholder input, even if indirect, can have justice implications, both procedural and distributive. This echoes observations by other studies, of the interdependences between the three tenets: embedding values into model logic shapes not just how decisions are made, but also what kinds of distributive outcomes are possible ([Vågerö and Zeyringer, 2023](#); [Giang et al., 2024](#)). We extend this discussion to recognition justice in [Section 4.3](#).

We discuss some examples of studies in this category. [Weinand et al. \(2021\)](#) use crowd-sourced “scenicness” data to represent public preferences for landscape aesthetics, incorporating these as spatial constraints to avoid siting infrastructure in visually valued areas. [Bolwig et al. \(2020\)](#) model public resistance to transmission lines by treating delays and mitigation efforts as additional system costs, thus integrating societal acceptability into infrastructure planning. Similarly, [Fitiwi et al. \(2020\)](#), [Koecklin et al. \(2021\)](#), and [Grimsrud et al. \(2021\)](#) include stakeholder priorities through penalty functions for environmental and social externalities, such as restricting siting in conflicted or sensitive locations. In another approach, [Lombardi et al. \(2020\)](#), [Neumann \(2021\)](#), and [Chen et al. \(2022\)](#) use MGA technique to explore near-optimal solutions that better reflect local values regarding land use, equity, or regional autonomy. While these examples were discussed earlier in the context of distributive justice ([Section 4.1.1](#)), their incorporation of societal values – albeit indirectly – also makes them relevant cases of procedural justice in model design.

4.3. Recognition justice

Recognition justice concerns the acknowledgement and fair representation of diverse identities, values, needs, and knowledge systems – particularly of those who are systemically marginalized – in the modelling of energy transitions ([Williams and Doyon, 2019](#)). In participatory contexts, it can relate to who is invited and represented in the modelling process, how meaningfully they are included, and whether the modelling activities and outputs respect and respond to their lived experiences and perspectives. Recognition justice differs from procedural justice in that it addresses inclusion from a structural and relational perspective; that is, it considers not just whether participation occurs, but whether the social, cultural, and political conditions allow all groups to be seen and heard as equals ([van Uffelen, 2022](#)). While procedural justice emphasizes the fairness of process, recognition justice highlights the need to address deeper patterns of misrecognition, marginalization, or exclusion that may be built into institutional practices and norms. Two guiding principles often associated with recognition justice are participatory parity – the idea that all individuals should be able to participate on equal footing in social interactions – and self-realization, which refers to individuals and groups having the opportunity to express and develop their own identities, values, and goals, free from domination or misrepresentation ([Fraser, 2023](#); [Honneth, 1996](#); [van Uffelen, 2022](#)). In modelling contexts, this can mean actively reaching out to communities that are often excluded from energy planning and ensuring they have not only the opportunity but also the material and symbolic resources such as time, funding, translation support, or technical assistance, to engage meaningfully on their own terms and shape their vision of the energy transition.

4.3.1. (Mis)recognition in the modelling process and participatory parity

Several studies address recognition justice by structuring modelling processes to be more inclusive of underrepresented voices and more sensitive to power and information asymmetries. This includes who is invited to participate, whether their input is meaningfully incorporated, and how barriers to participation such as technical knowledge, time, or cultural norms are addressed.

McKenna et al. (2018) explicitly focus on small communities typically excluded from formal energy planning due to lack of expertise or institutional support. Their framework combines MCDA, value-focused thinking, and optimization models to co-develop energy concepts that reflect locally prioritized values like autonomy and environmental sustainability. The participatory process is designed to overcome technical and institutional barriers, reflecting an explicit commitment to avoid misrecognition and enable meaningful participation.

Heaslip and Fahy (2018) develop energy scenarios based on community narratives from residents of Inis Oírr, an island community in West Ireland. Their participatory workshops elicit lived experiences related to energy access and infrastructure, which are then translated into modelled scenarios using the HOMER optimization-simulation model. One scenario, for instance, incorporates concerns about waste transport and infrastructure maintenance challenges specific to island life. This approach enables community members to see their realities and values reflected in the modelled options, helping bridge the gap between technical and lived-experience knowledge. Similarly, Krzywoszynska et al. (2016) engage community members in energy visioning workshops using maps, tactile physical models of the locality, and visual storytelling. The scenarios developed are consequently explored using an energy system model to understand impacts to the energy system. This mixed-methods approach allows residents to articulate knowledge that might not be easily expressed for integration into an optimization model. The authors also add a layer of modeller-reflexivity to the study results, by reflecting on whose knowledge has been included, the demographic composition of participants and acknowledging the bias that could be involved in the resulting visions.

These studies illustrate recognition justice as a design principle for participation in modelling processes, not just in terms of who is present, but in how participation is structured to elevate marginalized perspectives and ensure parity in involvement and decision-making.

4.3.2. (Mis)recognition in the model

Recognition justice can also be addressed through model structure and logic, through inclusion of structural inequalities, social and cultural heterogeneity for example. Several studies adopt this approach without participatory processes, instead relying on empirical data or social theory to shape assumptions and scenarios. For instance, Rahut et al. (2024) use regression and logit models to analyze how caste, gender, and rural/urban status influence access to clean energy in India. Their work highlights how systemic discrimination is embedded in energy access patterns, and makes the case for treating these social categories as critical variables in energy transition modelling. Similarly, Ding et al. (2023) use a statistical technique called Geographical Detector Model (GDM) to explore how socio-demographic factors such as race, income, and education drive disparities in solar PV adoption both spatially and across societal groups. Gladkykh et al. (2021) incorporate aspects of recognition justice into their system dynamics model of electricity access in Sub-Saharan Africa. They design and simulate energy scenarios based on the three tenets of energy justice. In this context, recognition is represented by designing system configurations that prioritize accessibility for rural and remote communities, rather than reinforcing centralized infrastructure patterns that tend to marginalize them.

ABMs also offer a route to address considerations of recognition justice by simulating how agents experience and respond to energy transitions (de Wildt et al., 2020; de Wildt et al., 2021). de Wildt et al. (2020) use an agent-based modelling approach to anticipate the social acceptance of sustainable heating systems in urban districts. Rather than focusing on current acceptance levels, their model identifies potential value conflicts that may emerge over time in specific social settings, illustrating how changing values can lead to future resistance.

Recognition justice in models can also relate to how outputs are measured. The choice of indicators can reflect or obscure recognition concerns – showing that this choice has implications not just for distributive justice but also recognition. For example, Finley-Brook and Holloman (2016) examine how the needs of marginalized communities are routinely overlooked in energy transition planning. They show that standard metrics fail to capture the specific vulnerabilities of low-income communities and communities of colour, thereby perpetuating patterns of misrecognition even in ostensibly “equitable” distribution analyses. Together, these studies show how recognition justice is not only a matter of who is included in participatory processes, but also how social structures, identities, and forms of marginalization are acknowledged or ignored within the technical logic of models.

4.3.3. Self-realization

Self-realization, as framed in recognition justice theory, refers to the ability of individuals and communities to develop and sustain a positive practical relation to themselves, grounded in being recognized as legitimate, capable, and socially valued contributors to collective life (Honneth, 1996). In the context of energy modelling, this can translate to designing modelling processes that do not merely include communities performatively, but by enabling them to see their knowledge, values, and aspirations meaningfully reflected in both the process and its outcomes. This includes creating space for underrepresented groups to challenge dominant narratives, co-construct scenarios, and see themselves as capable agents of energy system change - not merely as passive recipients of modelled futures.

While no study in our review explicitly adopts a self-realization lens, a few participatory modelling efforts implicitly touch on this principle. Once again, we bring in examples of Krzywoszynska et al. (2016) and Heaslip and Fahy (2018). In Krzywoszynska et al., community members co-develop narratives of desirable energy futures, which are then linked to modelling processes shaped around their framing, rather than the other way around which is more common, where narratives are gathered after the choice of model. The

use of tactile tools such as physical models aims to elicit situated understandings of energy and place, supporting a more expressive form of engagement. Heaslip & Fahy build their modelling on island-specific cultural and infrastructural narratives gathered through local engagement, employing varying levels of stakeholder involvement. For example, focus groups are used to collectively revisit and reshape participants' views on energy, while individual problem-centred interviews are used to recover personal, context-specific energy knowledge. Although community dynamics are an important theme in their research, they deliberately use the individual as the primary unit of analysis. Much of the discussion on local knowledge centres on the challenges faced by island residents, with participants' narratives revealing that geographic remoteness impacted how they perceive and practice energy use. The resulting energy scenarios reflect the way the islanders' unique place-based relations shape their understanding of energy transition for their community. For instance, the third technical scenario reflects participant accounts describing how remoteness affects the maintenance of technologies and daily life. One such challenge involves waste management, where disposal is costly and logistically demanding, requiring sea transport that also increases associated emissions.

These examples can be interpreted as interesting approaches to the concept of recognition through the principle of self-realization; however, the extent to which these efforts actually enable self-realization is difficult to assess, given the lack of evaluative steps. A tabular summary of results is found in [Table 7](#).

5. Discussion

In this section, we discuss key insights that emerge from our review of how energy models engage with distributive, procedural, and recognition justice. We begin by reflecting on empirical patterns observed across the studies reviewed, then explore their broader implications for conceptualizing the relationship between justice and energy modelling.

5.1. Limits of justice metrics

Justice often manifests in models as what can be quantified or measured within/by the model itself. Many of the studies reviewed, address justice through measures of cost distribution, spatial and societal distribution of burdens related to installation of RE infrastructure, often using Gini-coefficient as a metric for evaluating distributive equity. Such quantifications serve useful purposes, enabling comparability and allowing trade-offs to be analysed within computational models. This however also has limitations. We found no explicit modelling efforts that engaged with inter-species justice; that is, the distribution of energy-related burdens and benefits across human and non-human subjects. This dimension, though emphasized in energy justice scholarship (e.g., [Bossert \(2024\)](#), [Coeckelbergh \(2009\)](#), [Nussbaum \(2020\)](#)), remains absent from quantitative modelling practices, likely due to challenges in formalizing non-human impacts within energy system boundaries. Even when represented, they are done so from the anthropocentric point of view, such as particulate matter emissions, soil pollution, impacts to landscape or land-use patterns.

Furthermore, most models operate within static or short-term time horizons, with little attention paid to how burdens and benefits might be distributed across generations or how historical injustices might be addressed through compensatory measures. As a result, intergenerational dimensions of justice, such as long-term risks and burdens, remain unaddressed. Examples do exist and they demonstrate that modelling tools can, in fact, represent such concerns ([Dennig et al., 2015](#); [Woodward, 2000](#)). When long-term

Table 7

Overview of how models address recognition justice considerations.

Recognition justice	Focus	Approach	Examples of studies
(Mis-) recognition in modelling process and participatory parity	Combining MCDA + optimization + value-focused thinking to include community values	MCDA and optimization are used to build energy concepts that reflect priorities like local autonomy and sustainability	(McKenna et al., 2018)
	Using community narratives as the basis for scenarios explored through optimization and simulation models	Participatory workshops gather energy transition narratives, which inform model scenarios.	(Heaslip and Fahy, 2018; Krzywoszynska et al., 2016)
	Focusing on underserved populations who want to be involved but lack resources and expertise	Participatory process explicitly designed to include underrepresented groups	(McKenna et al., 2018)
(Mis-) recognition in model	Using community narratives to model relationship between people and their place.	Community experiences and narratives are translated into technical energy scenarios using optimization and simulation models (e.g., HOMER)	(Heaslip and Fahy, 2018; Krzywoszynska et al., 2016)
	Designing energy scenarios that improve accessibility for vulnerable populations (rural, remote, energy-poor)	System dynamics and agent-based models simulate configurations that improve access for disadvantaged communities	(Gladkykh et al., 2021; de Wildt et al., 2020; de Wildt et al., 2021)
	Analyzing structural inequalities in energy access and designing configurations that ensure systemic access	Agent-based models used to identify unequal capabilities and anticipate exclusion from decentralized energy systems	(de Wildt et al., 2020)
		Statistical models (e.g., logit, regression) assess the influence of caste, gender, and other social factors on energy access	(Ding et al., 2023; Rahut et al., 2024)
Self-realization principle	Centering community agency in scenario building. Local aspirations and visions are foundational assumptions for model	Community informs the structure and outcomes of the model.	(Heaslip and Fahy, 2018; Krzywoszynska et al., 2016)

impacts are omitted or stakeholders are not given the option to prioritize them in models during engagement moments such as research design or model conceptualization, certain outcomes may be implicitly prioritized over others. Such choices can be shaped by computational constraints of the model itself, resource constraints (how much time, financial and human resources are available), problem scoping, stakeholder selection and the level of engagement that the process allows (Giang et al., 2024). When these trade-offs remain implicit, the resulting model outputs may be mistakenly perceived as neutral or complete, obscuring the fact that unmodelled justice concerns – such as intergenerational, historical, or systemic injustices, were deprioritized, not irrelevant. Sharma et al. (2020) illustrate how being explicit about this, can prompt critical reflection on the justice implications of a model's structural limitations. In their case they reflect on how the Irish TIMES model could only incorporate aspects that were quantifiable, thereby excluding considerations such as social welfare that could not be operationalized with the model. These gaps point to a broader point of reflection: that, the logic and structure of the model and what it can quantify, can determine what justice aspects can be included. Which in turn can potentially reinforce a narrow conception of justice focused on distributive outcomes, sidelining concerns around process and recognition such as information asymmetries, systemic exclusion, or unequal power dynamics in participatory processes (Giang et al., 2024; Maas et al., 2022).

This leads us to our first recommendation: *when linking models to justice, modellers and model users should look beyond model logic and engage with the broader processes of modelling and model use and how decisions made therein can have justice implications.*

5.2. Participation is necessary but not sufficient

Our review shows that promising steps are being taken towards making models and their use in decision-making more transparent and inclusive of diverse stakeholder perspectives, reflecting a growing commitment to incorporating principles of procedural justice. However, several limitations still exist. First, participation is predominantly of the consultation nature, with several engagements being one-off and stakeholders having limited influence over model assumptions, purpose, or use of the model. Stakeholders are mostly invited to react to predefined problems, and less for co-defining what should be modelled in the first place.

Here, we can question to what extent mere presence of participation in modelling, do justice to procedural or recognition aspects in models. As discussed in the Section 2.1, procedural justice concerns principles that are applied to the design of participatory processes, such as transparency, inclusivity, accessibility. The design and implementation of participatory processes – including who is involved, when, and how their input is integrated – play a critical role. Several studies that we reviewed, limited participation to late-stage validation or scenario evaluation, with just one study co-designing the model structure or assumptions (Olabisi et al., 2010). More often than not, stakeholders were treated more as sources of data than as co-creators of the model/modelling process. Of course, this is not to say all modelling processes can or should involve full stakeholder participation at every stage. Time, funding, political constraints, and stakeholder preferences often limit the extent of engagement (McGookin et al., 2024). However, it is essential to recognize that the scope of stakeholder involvement is shaped by early-stage decisions, such as those made during research funding, problem scoping, research design and model development, which influence what kind of participation is possible or prioritized (Giang et al., 2024).

Recognition justice remains the least examined of the three justice tenets. Nonetheless, the application of our detailed coding framework helped us identify more studies incorporating elements of recognition justice than reported in previous reviews. While procedural justice is about who is involved and how they are included, recognition is about enabling inclusion by addressing the systems that marginalize certain perspectives or render them invisible. This means questioning who gets to define the modelling problem, whose knowledge is valued, and which categories and assumptions are embedded in the model (Giang et al., 2024). Given its systemic lens, addressing recognition justice in models requires modellers and model users to engage in a deeper rethinking of what the modelling is for and what its underlying assumptions and biases are. Once again, it is important to consider early decisions in the modelling process when decisions are made such as who frames the problem, which values or knowledge systems are prioritized. Studies like (Rahut et al., 2024; McKenna et al., 2018; Krzywoszynska et al., 2016; Gładkykh et al., 2021), are good examples that show how recognition is built into the early stages, beginning with the framing of the research aims, preceding steps where choice of the model is determined or the research design stage. These studies made deliberate early-stage choices to prioritize marginalized voices, center community-defined goals, and design for local autonomy. These further influenced the type of model that could be used to address the justice-centered research goals. Likewise, some studies show how stakeholder selection can be a normative decision, demonstrating how the inclusion or exclusion of specific communities or perspectives early in the process shapes which forms of recognition (or misrecognition) the model can account for (Sharma et al. (2020), Heaslip and Fahy (2018), Olabisi et al. (2010).

Even methodological choices such as whether to use optimization, statistical modelling, or participatory mapping, constrain or enable certain justice questions (e.g., Rahut et al. (2024), Schinko et al. (2019), Bernardo and D'Alessandro (2019)). Here, it is important to acknowledge that these decisions and choices are not made in a vacuum, but are shaped by broader institutional and political-economic contexts. Funding structures, political climate and institutional norms can constrain what questions are asked, whether and if so which justice concerns are prioritized, and whose knowledge or values are considered legitimate. As models are often commissioned or developed within technocratic systems, their ability to challenge the very power structures and systems that (re-) produce injustices of recognition, can be limited (Klenk, 2021). It is not to say that this embeddedness makes justice-oriented modelling impossible, but to emphasize the need for being explicit and critical about the institutional conditions under which modelling takes place and the power relations it may reproduce (Saltelli et al., 2020). Recognizing these structural limitations is important as we take steps to further link models and energy justice.

This brings us to our second recommendation: *modellers and model users should consider the justice implications of decisions throughout the modelling process that includes earlier stages where impactful decisions are made such as funding and resource allocation, problem scoping,*

research team formation, research design and stakeholder selection. These steps precede the modelling process as is conventionally understood, focusing mostly on the technical stages of model conceptualization, data collection, modelling building, verification and validation.

Vågerö and Zeyringer (2023) for instance, adopt the three-stage framework by Krumm et al. (2022) in their analysis that implementation of justice aspects can happen in any one of the stages of modelling: storylines & scenarios at input, in the modelling structure itself or through the discussion of modelling results. We believe this is still not sufficient as it overlooks justice-related aspects that are already shaped prior to the input stage, such as research design, stakeholder selection, and the influence of funding and time constraints on what the model can address. The scope of the modelling process therefore needs to extend further back to these early, impactful stages. Inclusion of these additional steps can influence how procedural and recognition justice can be addressed by models. For instance, in the problem definition and scoping stage, funding, time and resource constraints can influence the geographical, temporal and disciplinary scope of the model. This in turn can already determine what justice concerns can be addressed and whose concerns are seen as worth addressing. Further, when the modelling team or the research/project team is determined, the backgrounds of the modellers and whether their members of the team have backgrounds such as from social sciences or philosophy can influence what kind of modelling approach is selected and can influence choices regarding research design (McGookin et al., 2024). In the research design stage, choice of methodology, data sources, can structure what kinds of justice questions can (and cannot) be asked. Decisions regarding whether the study is participatory, and whether that participation is restricted to experts alone, or if residents and laypersons' inputs are also included- such decisions are influenced not just by funding or time constraints, but also by the composition of the research team.

Operationalizing this recommendation in practical settings can involve careful documentation of the process, including who made certain decisions or design choices, at what stage, for what reasons, and through which methods. While documentation is important, structured tools such as checklists, questionnaires and reflection guides, can facilitate critical reflection, supporting the team in examining the justice implications of their choices both process and model related. This can involve outlining key questions and considerations to be kept in mind, at each stage of the modelling process: from problem framing and team formation to data selection, model design, and communication of results. For instance, they can prompt teams to reflect on who defined the problem, whose knowledge or values are represented in model assumptions, or how stakeholder inclusion and transparency are handled in later stages and what implications these have in how the model is used. Such checklists or guides should be developed by drawing on best practices and lessons from previous studies that have engaged with justice considerations in modelling. This is not to suggest a fixed blue-print for all processes – the form of these tools may vary across contexts – but their purpose would be to make explicit how technical and processual choices shape what kinds of justice concerns can be addressed or are potentially overlooked. These ideas are interlinked with the next recommendation, which focuses on the role of modeller reflexivity and responsibility in shaping model design, its interpretation, and use.

5.3. Responsibility and reflexivity of modellers

It is important to note that these additional early-stage steps do not define justice in models solely in terms of participation. We emphasize that aspects of procedural and recognition justice, which are often related to the process of modelling, are equally relevant in modelling efforts that are not participatory. This pertains to modeller reflections on how assumptions are formed, how decisions are justified, and how transparency, accountability, and inclusivity are handled throughout the process. For instance, simplified tools, like spreadsheets or dashboards, may reduce cognitive barriers, but may still have a bias in the way they reflect certain expert choices about what dimensions matter, what trade-offs to present, and what assumptions to show/hide. Several studies illustrate how modeller reflexivity – i.e., reflecting on one's own positionality and epistemological commitments – can have implications on what the model results are and how they can be interpreted (Giang et al., 2024; McKenna et al., 2018; Krzywoszynska et al., 2016; Williams et al., 2022). These, in turn, determine who is represented in the model, who can meaningfully engage with it, and how fair the resulting decisions are perceived to be.

This leads us to the third recommendation: *modellers and model users should critically examine their own role, assumptions, and influence in the modelling process*. Reflexivity is essential for recognizing the normative commitments embedded in technical choices. It also fosters more honest communication with decision-makers about what the model can and cannot do, and what uncertainties or biases shape the results (Maas et al., 2022).

In practice, this can take many forms but essentially starts with model developers and users asking critical questions at each stage of the modelling process. We list a few: *What was the motivation for making this model? How was the project/research team formed – who was selected and why? What were the motivations for making the project inter/trans-disciplinary (or not)? Who was involved in formulating the problem statement and scoping? Who is considered a 'stakeholder' and who makes this definition? Was the type of model already chosen? If so why?* A reflection guide, consisting of a set of reflective questions that model developers and users can ask themselves and each other, at different stages of the process, can help structure such inquiry. These reflections can be communicated as a positionality statement at the start of model documentation or policy reports, enabling others who use or interpret the results to understand the context, assumptions, and potential biases underlying them. This transparency may also prompt readers and decision-makers to engage more critically with model outputs, aware of the conditions under which they were produced and interpreted. At the same time, reflexivity need not be a solitary exercise. Because positionality involves examining assumptions that are often implicit or unintentional, reflexive practice can benefit from group settings. Guided reflexivity workshops, for example, can bring together model developers and users to collectively examine key assumptions and modelling choices, and to discuss their implications for inclusion, exclusion, and representation of different societal groups and perspectives.

5.4. Leveraging alternate modelling approaches

No single model can fully represent all dimensions of a just energy transition, which is characterized as a wicked problem (See [Section 1](#)). Rather, each modelling approach offers only a partial but potentially complementary perspective. Moving beyond a “one-model-fits-all” logic is essential, as the energy transition involves diverse publics, values, benefits, and harms that cannot be addressed through a singular modelling lens ([Cuppen et al., 2021](#); [Trutnevyte, 2016](#)). As [Sharma et al. \(2020\)](#) note, “*many of the points of disagreement from the stakeholder workshop could not be represented by a scenario ensemble spread owing to current limitation in the structure of the Irish TIMES model (e.g., whole energy system optimization rather than sub-sectoral or agent-based optimization).*” Similar limitations are observed by [Venturini et al. \(2019\)](#), who describe how integrating qualitative storylines into a deterministic mathematical model initiated a mutual exploration between distinct analytical worlds. While their cost-optimization framework could identify the least-cost combination of vehicle and fuel technologies given techno-economic assumptions, it could not capture important drivers such as consumer behaviour or infrastructure lock-in, leading to results that diverged from stakeholder expectations and expert judgement on how the transport sector might actually evolve. These examples illustrate how relying on a single modelling paradigm risk omitting key socio-technical dynamics.

Combining approaches, such as coupling optimization with agent-based, game-theoretic, or system dynamics models, or using hybrid optimization–simulation tools to inform scenario framing, can open promising pathways for more accessible and inclusive processes. A related strategy is multi-modelling, understood as a set of interacting models, each representing a specific part of reality from a distinct perspective, and together providing stakeholders with a coherent, formalised, and reproducible representation of a system and its dynamics ([Cuppen et al., 2021](#); [Bollinger et al., 2015](#)). [Bollinger et al. \(2018\)](#) review several energy-domain initiatives adopting this approach and illuminate two strategies for multi-modelling approaches: one that emphasizes interoperability, enabling more efficient integration across scales and disciplines and facilitating systematic testing of assumptions; and another that values diversity – bringing together models from varied perspectives to bridge disciplinary silos and enrich understanding in the gaps between knowledge communities. We especially emphasise the value of the diversity strategy, leveraging the complementary strengths of different modelling approaches, as we build up to our fourth recommendation: *modellers and model users should consider using or combining multiple modelling approaches to address the complexity and multi-dimensional nature of decision-support for just energy transitions.*

While multi-modelling holds promise for addressing the diversity of justice aspects, it also introduces significant practical and epistemological challenges that must be acknowledged. Integrating multiple models can require considerable computational and human resources, which are subject to funding and time constraints. Moreover, combining models based on different epistemological assumptions can create tensions between analytical coherence and epistemological diversity. As [Watts \(2017\)](#) argues, even two similar models of collective behaviours in society, with the same empirical motivations can be logically incompatible, illustrating the problem of incoherency when applying modelling approaches in the social sciences. Similarly, when linking techno-economic and agent-based models, each operating with distinct formalisms, temporal resolutions, and spatial scales – the aggregation of results can lead to the amplification of uncertainties and inconsistencies across results ([Bankes, 1993](#)). These challenges underscore that multi-modelling should be viewed not as a definitive solution for addressing justice in models, but as a strategy for selectively leveraging the complementary strengths of different modelling approaches to capture justice dimensions that single models cannot.

6. Conclusion

This paper set out to answer the question: *How do current energy models address distributive, procedural, and recognition justice, and what changes are needed to enhance their ability to support justice-oriented decision-making?* To this end, we conducted a structured review of $N = 63$ peer-reviewed modelling studies, using a detailed coding framework grounded in energy justice theory. With regards to the first part of the question, our analysis finds that the dominant approach to linking justice and models is the incorporation of justice considerations within model logic, with far less attention paid to how choices regarding the modelling process itself influence a model’s capacity to address justice. Across modelling approaches, aspects of justice that are more easily quantified and formalised tend to be prioritised, which aligns more closely with distributive concerns. Within distributive justice, societal and spatial dimensions are most frequently addressed, while only one study considered the distribution of impacts over time into the future. Restorative or compensatory notions of distributive justice are not addressed in the studies reviewed by us. Within societal impacts, only human impacts are considered by models, leaving out impacts to non-human subjects such as flora and fauna. In terms of procedural justice, there are promising steps taken to include stakeholders in defining qualitative scenarios, determining evaluative indicators and metrics through the use of methods such as MCDA/MCA. The way they are engaged ranges from surveys and interview to focus groups and workshops. Studies variously address principles of procedural justice such as transparency and inclusivity of processes by which they are involved in modelling, and of the model itself, for instance through simplification of complex models or use of interactive models for use in participatory processes. Most studies address procedural justice through the broad lens of involving stakeholders, with limited attention to or reflection of whether these engagements are sufficient or meaningful for the stakeholders involved, to be able to express their concerns. Although we align with previous reviews regarding the fact that recognition justice is least addressed, our detailed coding framework and inclusion of other modelling paradigms taps out more number of studies as addressing aspects of recognition justice, albeit implicitly. Studies typically use non-optimisation approaches such as simulation, agent-based, system dynamics, and statistical models to address systemic inequalities and injustices faced by vulnerable groups in accessing the energy transition.

Drawing on these findings, we propose four interlinked recommendations for modellers and model users interested in engaging with energy justice, thereby addressing the second part of the research question: first, move beyond a sole focus on model logic to also

consider the broader processes of modelling and model use; second, integrate justice considerations throughout the entire modelling process, including early-stage decisions on funding, resource allocation, problem scoping, research team formation, and stakeholder selection; third, adopt a reflexive stance that critically examines the modeller's own role, assumptions, and influence; and fourth, explore the use or combination of multiple modelling approaches to better address the multi-dimensionality of energy justice.

Future work is needed to test and refine whether greater attention to justice during model development, framing, and use results in more just outcomes in practice. Within the JustETrans project, we apply these recommendations in empirical settings, designing and facilitating participatory modelling processes to support local energy transition planning, and organising workshops with modellers and model users. This work will allow us to iteratively refine the recommendations in response to the practical constraints and justice requirements of model-based energy transition planning.

CRedit authorship contribution statement

Aarthi Sundaram: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yilin Huang:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Igor Nikolic:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Eefje Cuppen:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Supplementary materials

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Data availability

Refer to Supplementary Material attached.

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