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Operationalizing justice in models used as decision-support tools in local and regional energy transition planning

Aarthi Sundaram[1,*], Yilin Huang[1], Eefje Cuppen[2,3] and Igor Nikolic[1]

[1]Faculty of Technology Policy Management, Delft University of Technology, The Netherlands
[2]Faculty of Governance and Global Affairs, Leiden University, The Netherlands
[3]Rathenau Instituut, The Netherlands

[*]Corresponding author. Email address: a.meenakshisundaram@tudelft.nl

Abstract

It is widely considered that the energy transition should be just, yet achieving this goal is a complex socio-technical process. Models serve as valuable tools to support decision-making in navigating these complexities. However, they are not adequately equipped to address justice considerations that are becoming central to energy transition planning. They are unable to provide support in decision spaces that are rich in normative uncertainties, with stakeholders holding differing interpretations of what a just energy transition is. While the importance of integrating justice into computational models is recognized, a significant gap remains in understanding how justice is and can be defined, interpreted, and implemented within these models or, in short, how justice can be operationalized. This paper addresses the gap by examining studies that use computational models for decision-support through the lens of the three tenets of energy justice: procedural, recognition, and distributive justice. We argue that operationalizing justice in energy transition modelling can take place both in the modeling process and with the enrichment of model logic. This paper emphasizes that discussions of justice in relation to models cannot be separated from the design of effective participatory modelling settings that stem from a careful evaluation of the justice requirements of stakeholders in the decision space. We propose a framework that enables modellers and model users to be more explicit about their normative interpretations of justice and derive modelling processes and model requirements that represent diverse justice perceptions in the decision space. By doing this, models can refrain from propagating only dominant ideas of justice and instead actively incorporate otherwise neglected perceptions, to ensure that the decision-support facilitates a just energy transition.

Keywords: Energy Justice, Computational Models, Energy Transition, Decision-support

1. Introduction

The pursuit of the Paris Agreement goals by governments involves a significant shift towards a fossil fuel-free future and is often referred to as the energy transition (Harichandan et al., 2022). This transition should not only aim to reduce greenhouse gas emissions but also ensure that the goals are achieved in a just way (Sonja & Harald, 2018). In recent years, protests against energy policies have increased as people feel marginalized, unheard, or threatened by changes that affect their way of life (Scherhaufer et al., 2021). This calls for policies that are inclusive of the perspectives and differential abilities of all those impacted by the energy transition (Dennig et al., 2015). The energy transition needs to be just.

Achieving a just energy transition is complex due to the involvement of many stakeholders with different resources and interests, such as national and local governments, energy producers, grid operators, industries, and residents. Establishing coordination and consensus among these actors is crucial for making informed decisions (Newell & Mulvaney, 2013). The process is further complicated by social factors and uncertainties that significantly impact energy infrastructure planning (Haas et al., 2023). This planning is characterized by deep uncertainty, influenced not only by physical constraints but also by factors such as public acceptance, land use, and impacts on the local environment and biodiversity. Consequently, decision-making within this complex system often relies on computational models and simulations to navigate these uncertainties (Horschig & Thrän, 2017).

Energy transition models used in the decision-arena are often techno-economic models that are not adequately equipped to incorporate social aspects such as justice (Chang et al., 2021). In the context of a global imperative for a just energy transition, this paper delves into the often overlooked yet pivotal aspect of operationalizing justice considerations within computational models.

Despite a growing body of literature exploring justice in the energy transition, there remains a distinct gap in our understanding of how justice concepts are defined, interpreted, and ultimately implemented in computational models that support energy transition. As the use of models for decision-support in energy transition becomes increasingly prevalent, there is a growing need for these models to reflect the justice requirements of the decision-making space which is often value-diverse and multi-stakeholder (Vågerö & Zeyringer, 2023).

Recent reviews of modeling efforts in the energy transition domain have focused on the extent and quality of integration of justice considerations (Sonja & Harald, 2018; Krumm et al., 2022; Lonergan et al., 2023; Vågerö & Zeyringer, 2023). However, it is still not clear how justice tenets such as procedural justice or recognition justice are defined, interpreted, and operationalized within the computational models and in the modelling process. Furthermore, discussions at the intersection of energy justice and energy transition modeling have been limited to Energy System Optimization Models (ESOMs) (Lonergan et al., 2023; Vågerö & Zeyringer, 2023). This leaves out the potential advantages of other modeling methods such as Agent-based Models (ABMs) or Systems Dynamics (SD) models that can be leveraged to improve representations of justice in the decision space (Dall-Orsoletta et al., 2022; T. G. Williams et al., 2022).

We address this gap by adopting the framework of three tenets of justice—procedural, recognition, and distributive—as a lens to analyze computational modeling studies that explicitly consider justice issues of the decision space. We make explicit, the definitions of justice tenets, their interpretations in empirical contexts at a local and regional level where models are used as decision-support tools, and subsequent implementations of justice in these models. This analysis aims to reveal the varied interpretations of justice and how they influence operationalizations in computational models. In addition to elucidating the current landscape, the paper also offers tangible initial recommendations for operationalizing normative interpretations of justice in models, to improve decision-support for the energy transition at the local and regional level.

2. Normative interpretations of tenets of justice

Justice is becoming central to shaping energy transition strategies at local, national, and global levels (McCauley & Heffron, 2018). This is reflected within the academic discourse on energy transition, with an increasing number of studies using popular frameworks such as the three-tenets of justice and the ten principles of justice (Lee & Byrne, 2019; McCauley et al., 2013; Sovacool, 2017). These frameworks offer generic and context-agnostic definitions of energy justice and function as useful conceptual and analytical tools (Sovacool & Dworkin, 2015).

In empirical studies, the highly contextual nature of justice becomes pronounced within real-life decision-support spaces characterized by normative uncertainties (Van Uffelen et al., 2024). Normative uncertainties stem from normative diversity when there are multiple legitimate interpretations of the same justice concept, of what is or should be "just" or "fair" (Taebi et al., 2020). Different stakeholders can disagree on whether a decision-making procedure is just and can have different perceptions of what is a just distribution of costs and benefits (Gaus, 2016). These diverse normative interpretations, created by differing perceptions of the same justice tenet, necessitate explicit substantiation (Van Uffelen et al., 2024; Wood & Roelich, 2020). By making normative interpretations of what is "just" or "fair" explicit, and critically evaluating underlying motivations and values can help curtail the perpetuation of status-quo, apparently objective rules that can reinforce social injustices (Collins et al., 2021; Silver, 2021). In the following sub-sections, we map out different normative interpretations of the three tenets of justice: procedural, distributive and recognition justice.

2.1. Procedural justice principles

The tenet of procedural justice is broadly defined as "concerning inclusion or exclusion in decision-making process concerning energy transition" (Walker, 2012). This is a generic definition that does not make explicit what makes the procedure just or unjust. Empirical studies, implicitly or explicitly, have a normative interpretation of the justice tenet, often following a generic formulation of "procedure is (un-) just if *X*" (Van Uffelen et al., 2024). For example, a procedure can be deemed by a group of actors to be just if it follows due process. For another group, a just procedure is one that empowers the community and to some others it can mean transparency and accountability. Some normative interpretations of procedural justice discussed in energy justice literature include: a) *All-affected principle*: whereby a procedure is just if it provides a voice to marginalized and vulnerable members of society impacted by the energy transition decision, through a seat at the table or through a representative (Miller, 2017); b) *Transparency and Accountability*: whereby a just procedure is one that ensures transparent decision-making, one that reduces information asymmetry through good communication, provides access to high quality information to all people and ensures formal accountability mechanisms such as an independent ombudsperson to address grievances and feedback (Sovacool et al., 2017); c) *Due-process:* whereby the procedure is just if everyone is treated equally, in an unbiased manner, in accordance with established rules and legislation; d) *Community/Local empowerment*: whereby the procedure is just if it puts the community in the center of decision-making, incorporates local knowledge, ensures that the process reflects local values, and makes clear what the benefits and impacts of the energy transition decision are, to the locality (Sovacool et al, 2017). The latter could encompass tailoring the process to respect religious procedures or indigenous decision-making practices unique to the locality (Van Uffelen et al., 2024).

2.2. Distributive justice principles

Broadly defined, distributive justice concerns "distribution or allocation of good (resources) and bad (harms and risks)" (S. Williams & Doyon, 2019). Some normative principles that according to which a given distribution is deemed just/unjust are: a) *Utilitarianism*, whereby a just distribution distributes the greatest good to the greatest number (Myerson, 1981); b) *Egalitarianism* (according to Rawls' difference principle) whereby a distribution is unjust if some people are left worse off than others (Rawls, 1999); c) *Sufficientarianism*, by which the distribution is unjust if it leaves some people without enough resources (good/benefits of the transition) (Miller, 2017); d) *Prioritarianism*, whereby a just distribution maximizes the sum of welfare that is weighted to ensure that benefits at lower levels of welfare have more weight than those at higher levels (Adler & Holtug, 2019).

In empirical studies however, there is lesser focus on *principles* of distribution and more on intersecting dimensions such as vulnerability, responsibility at spatial and temporal scales (Walker, 2012). Distributive justice concerns are about affordability, availability, and accessibility of clean energy sources to vulnerable groups, unequal distributions of impacts spatially and temporally to both human and non-human members (S. Williams & Doyon, 2019). We want to clarify that, ultimately, distributive principles such as egalitarianism or utilitarianism underlie many justice considerations such as affordability, accessibility, availability and sustainability, but these are not made explicit. Sasse & Trutnevyte (2019) provide a useful framework that groups distributive justice considerations into three dimensions: distributions across space, society and time. We use that to group normative interpretations of distributive justice commonly found in empirical contexts:

Across space, a distribution can be unjust if benefits (such as electricity access, lower electricity prices, reliable energy supply) and costs (such as inconveniences and changes to the landscape due to energy infrastructure construction, loss of jobs due to decommissioning of fossil-fuel energy projects) are unequally distributed across geographical space (Ghosh et al., 2023; Sareen, 2021; Sasse & Trutnevyte, 2020). People who live closer to the construction of new energy infrastructure may perceive distributions unjust as they bear the burdens while the benefits of the produced energy are experienced by those who live away from the site; these are conflicts that often arise in the siting of large-scale wind and solar (O'Neil, 2021). Cosmopolitanism is a spatial justice consideration, according to which the distribution is just if it considers the spill-over effects of the energy transition decision beyond the geographical constraints of the locality (McCauley et al., 2019).

Across society, distributions can be unjust if an energy transition decision disproportionately burdens lower-income members of society or excludes vulnerable groups from acquiring the benefits of access to cleaner energy options. For example, higher-income households are more likely to adopt rooftop solar PV panels, benefitting from lower electricity prices and cleaner energy, because they have access to more information, financing options, and social networks with adoption experience (Sundaram et al., 2024). Non-anthropocentric, biocentric, or eco-centric principles are normative distributive principles, as they consider negative impacts on biodiversity, the environment, and non-human members of society as unjust distributions (Sovacool et al., 2017).

Across time, also referred to as intergenerational justice, whereby an unjust distribution is one which unequally distributes benefits and burdens of the energy transition between generations today and in the future (Malakar et al., 2019). For example, accelerating resource depletion and unambitious climate mitigation strategies are examples of unjust distributions that unequally burden future generations. Through principles of restorative justice, distributions can be just if they compensate the environment and people for harm that has resulted from energy systems in the past (Hazrati & Heffron, 2021).

2.3. Recognition justice principles

This tenet concerns recognition, misrecognition, or non-recognition of various groups involved in the energy transition (Walker, 2012). It is conceived in terms of who is given respect and who is or isn't valued (S. Williams & Doyon, 2019). From the overview of recognition justice in the energy transition by van Uffelen et al. (2024), two principles of just recognition are identified from literature. *Fraser's principle of participatory parity*, whereby misrecognition is unjust as it prevents an actor from interacting as full peers in social life (Fraser, 2009). The other approach is *Honneth's principle of self-realization,* whereby recognition is just when it allows for an unharmed/undistorted relation to self; a person is self-confident and is aware of what they deserve through love, laws, and cultural appreciation (Honneth, 1996).

3. Model Operationalizations of justice

There are rich discussions in energy justice literature concerning the importance of being explicit about normative interpretations of these justice tenets and substantiating them (K. E. H. Jenkins et al., 2020; Van Uffelen et al., 2024). However, these discussions do not extend to the modeling literature, despite increasing applications of energy justice concepts in models that support energy transition decision-making. Having outlined commonly occurring normative interpretations in empirical contexts in the previous section, we now proceed to examine if and how computational models supporting decision-making address these concepts.

Methods: Firstly, we build an inventory of empirical studies published in peer-reviewed journals that a) concern decision-making in the energy transition, b) include a computational model that serve as one of the decision-support tools, c) the energy transition decision is made at a local or regional level and d) has a clear focus on including justice aspects of the decision-space into decision-support. By computational models, we mean those involving numerical processing, mapping between different variables and are programmed on a computer. This excludes surveys, data analysis, static maps, and serious games. To build this inventory, we start with two recent reviews that have been published, which survey the extent to which justice considerations of the energy transition have been included in energy models, more specifically, optimization models: Vågerö & Zeyringer (2023) and Lonergan et al. (2024). Given our focus is on computational models supporting decision-making, our scope expands beyond Energy System Optimization/Simulation models, to also include Agent-based Models, System Dynamics Models, Statistical and econometric models, that are used in supporting decision-making at the local and regional levels. We therefore include models reviewed by (Dall-Orsoletta et al., 2022) who focus on integrations of social aspects of energy transition within System Dynamics models, (McGookin et al., 2017) who review participatory modeling approaches and (Krumm et al., 2022) who evaluate the extent to which social aspects of the energy transition are included in Integrated Assessment Models (IAMs), ESOMs, Energy System Simulation Models (ESSMs), ABMs, SDs, Computational General Equilibrium (CGEs) employed in EU-HORIZON projects. The authors also add to this inventory to represent more recent results by running a keyword search on the Scopus database. 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*". Results were further filtered to include only peer-reviewed articles in the English language, which were published after 2009. The resulting papers were further screened by reading the abstracts to restrict focus to computational models used to support decision-making in the local and regional contexts, thereby excluding global and national models. In total, N=102 articles were selected for the final analysis. In the following sub-sections, we analyze whether and, if so, how computational models providing decision-support operationalize different interpretations of justice tenets.

3.1. Procedural justice

We find that procedural justice finds place in model-based decision support primarily through the concept of "social acceptance" of renewable energy projects/planning (related terms that are interchangeably used include public acceptance or community acceptance). According to Bidwell & Sovacool (2023), a big determinant of social acceptance is the perceived fairness or perceived justness of the procedure by which decisions are made, thereby causing overlap in literature discussing procedural justice and social acceptance. A decision-making process that meaningfully involves the locality and engages stakeholders early in the process itself, is recommended to build support and therefore improve acceptance of renewable energy projects (Liebe & Dobers, 2020). When decision-makers make efforts to prioritize the input and preferences of stakeholders throughout decision-making, they are likely to develop solutions that are perceived as socially acceptable. In turn it is assumed that stakeholders may view the decision-making process as fairer because their voices were heard and considered in shaping the outcomes. From our review of modelling studies however, we observe that the concepts of procedural justice and social acceptance are used interchangeably. The nature of their relationship and how they influence each other in decision-making, is not explicitly addressed, causing the connection between the two concepts to remain vague. Our analysis finds there are two broad angles that studies take, when operationalizing social acceptance and procedural justice in their models: a) Firstly, they model social acceptance as part of model logic, to identify socially acceptable outcomes that are assumed by default to be perceived as procedurally just by those impacted by the decision; b) Secondly, studies try to improve social acceptance of model outcomes by adopting a participatory modelling approach, which is assumed to improve stakeholders' perceptions of procedural justice.

Within model logic: In this first approach, perceptions of procedural justice are operationalized by aiming for social acceptance. ESOMs are the predominant model type here, using methods like Modelling to Generate Alternatives (MGA) or exploring near-optimal solutions beyond the least-cost ones. Social acceptance is quantified as additional costs to the total system cost. For example, Bolwig et al. (2020) use an ESOM to identify socially acceptable solutions by quantifying the costs of measures to cope with the lack of social acceptance and project delays. Other modeling approaches assume positive relationship between factors like minimizing land-conflict and social acceptance. Chen et al. (2022) use a spatially explicit ESOM to assign higher costs to conflict-prone areas and identify solutions that minimize opposition. label some technologies as "problematic" to identify energy mix scenarios facing the least opposition. For example, Price et al. (2022) and Weinand et al. (2022) use "scenicness" data to design scenarios sensitive to visual impacts, treating scenicness as a model constraint or objective function. Most studies do not explore what justice perceptions constitute social acceptance or how they influence public support and consequently do not directly engage with the procedural justice concept despite claiming to do so. For example, Koecklin et al (2021) explore implications of public acceptance for a wind energy project on total system costs by examining scenarios without discussing acceptance factors. Overall, modeling studies treat social acceptance as a means to an end, focusing on successful project implementation without considering how justice improves public support. This overlooks the intrinsic value of justice, potentially leading to less robust and less supported solutions (K. Jenkins et al., 2016).

Within modelling process: In the second approach, models incorporate stakeholder input via participatory methods to identify acceptable policy options. This approach uses various models, with methods like Multi-Criteria Analysis (MCA), Cognitive Mapping, Computer-based decision tools, and Statistical Choice-modelling.

Multi-Criteria Analysis (MCA) or Multi-Criteria Decision Analysis (MCDA) methods elicit stakeholder requirements and incorporate them into models. Trutnevyte et al. (2011) and Simoes et al. (2019) engage stakeholders to select criteria and weights, ensuring outcomes align with preferences. Wilkens (nee Braune) & Schmuck (2012) employ MCDA in Life-Cycle Assessment (LCA) modelling, utilizing software like GEMIC for evaluating the sustainability of energy scenarios based on a set of diverse criteria such as human toxicity, ecotoxicity, employment, perceived noise & smell, risk of accidents and independence from fossil energy resources. Cognitive mapping techniques involve stakeholders' perceptions and interactions to co-create models reflecting shared understandings. Düspohl et al. (2012) and Schmitt Olabisi et al. use this to integrate non-academic inputs into energy scenarios, fostering inclusivity and trust. Computer-based decision tools like those developed by Mayer et al. (2014) and Flacke and De Boer (2017) enable stakeholders to interact with model outcomes and express preferences. For example, COLLAGE, is an interactive planning-support tool that combines maps and digital visualizations to facilitate stakeholder decision-making. These tools have the advantage of soliciting direct individual preferences and feedback to rank preferred policy options while also serving as a communication tool that informs residents of the health, economic and environmental impact of their choices. Statistical choice modelling techniques, such as ordered probit and mixed-logit models, delve into stakeholders' motivations and values to understand policy acceptability. Choice modeling involves presenting participants with a set of alternative scenarios or policy options and asking them to make choices based on their preferences. Groh & Ziegler (2018) and Kanberger & Ziegler (2023) use these models to study citizens' acceptance of energy policy measures, revealing underlying factors influencing acceptance or opposition. Mouter et al. (2021) apply Participatory Value Evaluation (PVE) to elicit citizen input on strategic choices in energy transition planning, including their perspectives on fairness and justice.

These methods offer unique ways to incorporate stakeholder input and operationalize justice. Cognitive mapping is suited for non-dominant perspectives, while computer-based tools and choice modeling involve individuals directly in decision-making, improving participatory parity.

A significant gap exists between how procedural justice is conceptualized in theory and its application in models. Empirical studies focus on inclusivity, transparency, and accountability, while models limit procedural justice to participatory evaluations. McGookin et al. (2021) note a lack of collaboration with non-academic stakeholders and limited engagement. Most studies include only experts and institutional stakeholders, with few incorporating residents and local organizations. This approach often interprets procedural justice through the all-affected principle or community empowerment, aiming to include local context and non-dominant perspectives.

3.2. Distributive Justice

Distributive justice in the modelling context is addressed mainly through the spatial and society dimension, with the time dimension concerning distribution of impacts to future generations, generally ignored.

***Within model logic*:** There are several studies that combine the spatial and societal dimensions to evaluate spatial distribution or impacts of policy measures through socioeconomic indicators such as income, energy prices, employment, environmental impacts (Bertsch & Fichtner, 2016; Sasse & Trutnevyte, 2019; Wilkens (nee Braune) & Schmuck, 2012). Most of these studies involve Energy System Optimization Models (ESOMs), which are used to identify policy options that minimize measures of inequity like the Gini coefficient or, as a post-processing step, evaluate generated policy options on their inequity values.

A just spatial distribution is interpreted in different ways, ranging from equitable distribution of renewable energy generation infrastructures across space, equitable regional distribution of jobs that are created or lost due to the energy transition. A specific spatial allocation of energy infrastructures can be deemed as inequitable if some regions have a disproportionately large number of power plants, while other regions have significantly fewer or none at all. In such cases, stakeholders in regions where the energy infrastructure is contained, perceive this spatial allocation as unjust as they are overburdened with the environmental impacts associated with renewable energy infrastructure, such as land use or visual pollution, while the other regions only benefit from the economic opportunities and cleaner energy (Sareen, 2021). This inequity of distribution is commonly operationalized by studies using the Gini coefficient or the Lorenz curves. For example, Drechsler et al. (2017) determine spatial equity of different spatial allocations of renewable power plants by using Gini coefficient as a measure of equity. Sasse & Trutnevyte (2019) explore equity implications of distribution alternatives across regions on employment and land use change using Gini coefficient and Lorentz curve. Neumann (2021) measure regional distributive equity using Lorenz curve, by operationalizing "equity" as the ratio between total electricity generation and consumption and the Gini coefficient is used to determine the extent of (in-)equity.

While the studies above evaluate generated model outcomes for spatial equity, other studies identify alternatives that maximize for it, by making it part of the objective function. Grimsrud et al. (2021) maximize for "efficiency" of spatial distribution of new wind power plants, where efficiency is quantified as "lower social costs" and "lower environmental costs". Nock et al. (2020) on the other hand maximize for "social benefit" which is conceptualized as equality of energy access. This is operationalized in the model through the Gini coefficient and model outcomes that rank highest on this parameter are preferred.

Several studies post-process model outputs to assess impact of policy strategies based on sociodemographic or welfare indicators. Patrizio et al. (2018) for example, evaluate model outputs for their impact on jobs created or lost. Sasse & Trutnevyte (2020) post-process scenario output for impact on regional equity, employment and land use. In Wang et al. (2019), equity (Gini coefficient) of different target allocation schemes is measured. Environmental and health impacts of energy transition policies can be studied by evaluating them based on indicators such as air pollution, human toxicity potential and hazardous waste production (J.-J. Wang et al., 2009; Wilkens (nee Braune) & Schmuck, 2012). Distribution of impacts and benefits over time is the least explored dimension in modelling studies focused on the local level; this concurs with the lack of energy system simulation models in the studies reviewed. Even in participatory modeling studies where future energy scenarios are quantified together with stakeholders, intergenerational justice concerns do not appear to be part of the discussions.

***Within modelling process*:** In process of modelling, distributive justice considerations are operationalized primarily via stakeholder input in modelling choices. The question of "who" is invited to provide input can determine the choice of indicators or based on which model outputs are evaluated or ranked. Inclusion of stakeholders from non-energy related domains for example, brings in perspectives of health and cultural impacts of policy options, which then manifest in model logic through output metrics and model constraints (Schmitt Olabisi et al., 2010). It can be argued that operationalization of distributive justice within model logic, is contingent on explicit inclusion of justice considerations in the modelling process either by the modeler alone or in a participatory manner through stakeholder inclusion.

3.3. Recognition Justice

In modeling literature, recognition justice is the least discussed tenet. We observe that, operationalization of the recognition justice principles is very intimately tied to the design of the participatory modeling process and in that sense, closely linked to distributive justice in the modelling process. Recognition justice considerations in the studies reviewed, are addressed through the nature and quality of inclusion of actors and their unique backgrounds. Adaramola et al., (2017) and Eghbal et al., (2021) for example, acknowledge remote communities as facing specific social and energy challenges. Schmitt Olabisi et al., (2010) bring in non-dominant perspectives by including representations from outside the energy & environment field, such as religious and health institutions. As discussed in the procedural justice sub-section, particular methods of involving stakeholders in the participatory modelling process such as cognitive mapping or choice modelling / PVE, show potential for operationalizing interpretations of self-realization and participatory parity principles respectively. Cognitive mapping can facilitate self-realization by providing individuals with a structured framework to articulate their perspectives, experiences, and justice perceptions concerning the energy transition. Through exercises like causal diagramming, participants can explore and visualize the trade-offs and interconnectedness of various factors influencing the energy transition decision. This process can help individuals to gain insights into their own values, priorities, and goals, fostering a deeper understanding of themselves and their place within the transition process. By actively engaging in cognitive mapping, stakeholders can enhance their self-awareness and confidence, contributing to their ability to assert their needs and interests in decision-making processes.

Similarly, choice modeling can support the principle of participatory parity by ensuring that all stakeholders have an equal opportunity to express their preferences and priorities regarding energy transition options. This allows for the systematic elicitation of individuals' preferences, regardless of their socio-economic status or level of influence. By collecting and analyzing stakeholders' choices, decision-makers can identify what perceptions and factors play a signficant role in individual choices and incorporate these insights into decision-making in an equitable and inclusive process that is in line with the principle of participatory parity. Such approaches in current literature are very few, and in their approaches, they do not situate themselves in energy justice concepts (Groh & Ziegler, 2018; Kanberger & Ziegler, 2023).

4. Discussion and Recommendation

From our review of studies using models to provide decision-support for the energy transition, we observe that a critical distinction needs to be made between justice in the model versus in the modelling process. Justice considerations can manifest in models in two broad ways: a) justice considerations in the processes surrounding the development & use of the model and b) justice as it is implemented within the model itself, contained within the model logic in the form of model relationships, output metrics etc. In the context of regional and local level energy transition planning, participatory modelling approaches have been on the rise, where stakeholders are directly invited to provide input and take part in the modelling process. Studies that were reviewed took different strategies to involve stakeholders: some only invited experts & decision-makers, some included only members of the community, whereas some invited representatives from diverse expert groups, decision-makers as well as community members. This selection process of who gets to be involved, what its implications are for representations of justice considerations in decision-making is not justified by the researchers. Whether these design choices result from resource and time constraints, or whether they are motivated by the need to place justice considerations front and center in decision-making, is not clear. The ways by which input is sought, do not result from systematic design choices grounded in either participatory modelling research or guidelines. McGookin et al.

(2021) note that the meaningfulness of engagement in participatory modelling processes vary widely: from passive one-time interactions to deep involvement at each point in the modelling process where actors' input and feedback are sought from conceptualization phase up to model development and interpretation of results. From the perspective of inclusion of justice considerations however, it is not clear which of these design choices are effective. Even when some studies make the effort to bring together and incorporate diverse perspectives into the modelling process, the implications of these choices on the quality of justice considerations brought to decision-support are not examined. Do participants perceive the process more just after the inclusion of diverse perspectives? Or does it lead to more conflict and slow down the process of decision-making? Answers to these questions can improve design of participatory modelling process to better represent justice considerations in decision-making, but currently, they are unclear. Amongst the normative principles of procedural justice discussed in the research background section, only two principles are represented in the modelling literature, namely, the all-affected principle and the community empowerment principle. Equally relevant considerations such as transparency (of model and process), ensuring accountability and due process, do not find mention in the design and application of participatory modelling approaches currently.

We propose a conceptual framework, outlined in Table 1, that is designed to ensure that normative uncertainties in the decision-space are made explicit and diverse normative principles are adequately represented in both models and modelling processes. This framework aims to counteract the risk of outcomes that propagate dominant worldviews or justice perceptions, which may result in solutions that exacerbate inequalities and that are not accommodating of differential needs and vulnerabilities. Our proposed framework encourages modelers and model-users to explicitly consider and integrate normative principles throughout the modelling process and model logic. The framework is structured around three tenets of energy justice: procedural, recognition, and distributive justice. For each tenet, we outline specific normative principles and derive corresponding process and model requirements to ensure justice considerations are central to models used in energy transition planning.

Table 1. Proposed framework to derive model and process requirements to address normative interpretations of the three tenets of energy justice

Tenet	Normative Principles	Process Requirements	Model Requirements
Procedural	Principle 1	Process Req.	Model Req.
	Principle 2	Process Req.	Model Req.
	…		
Recognition	…		
Distributive	…		

***Within modelling processes*:** In operationalizing different principles of procedural justice within the modelling process, justice considerations that emerge include inclusivity, transparency, and adherence to due process. A modelling process that interprets procedural justice through the *all-affected principle* requires the inclusion of all relevant parties or their representatives in the modelling process, ensuring their perspectives are explicitly elicited and considered. Transparency and accountability can be maintained by designing the process to solicit and incorporate feedback iteratively from stakeholders at different stages. Transparency during deliberations, workshop sessions, and data processing can be reinforced by adhering to agreed-upon privacy regulations, throughout the modelling process.

In operationalizing normative interpretations of recognition justice within the modelling process, key considerations include, fostering participatory parity, self-realization, and fair representation. Although these concepts can mean differently to each stakeholder, a first step to operationalizing participatory parity can be ensuring that the modelling process respects and accommodates the unique requirements, identities, and vulnerabilities of each actor or representative present at the table, through pre-workshop surveys and semi-structured interviews (Mussehl et al., 2023). Additionally, an unbiased and neutral ombudsperson may be appointed to address grievances concerning participation in the process, to ensure a level ground for participation for energy-poor and previously marginalized voices (Hesselman & Tirado Herrero, 2020; Stojilovska, 2023). Self-realization can be facilitated by providing avenues within the modelling process for the elicitation of values and preferences of individuals, and through active efforts to welcome and incorporate non-dominant, non-western knowledge systems and worldviews. Methods such as cognitive maps and semi-structured interviews can allow individuals to discover and express their perceptions of what constitutes a just procedure or distribution based on their lived experiences (Guckian et al., 2018).

By being explicit about normative diversity of justice interpretations helps uncover non-dominant considerations (Silver, 2021). The resulting operationalization of multiple principles of distributive justice within the modelling process, provides avenues for exploring the impacts of multiple distributions of benefits and burdens in collaboration with stakeholders. By engaging stakeholders in the examination of alternative distributional scenarios, the modelling process can enable an assessment of the trade-offs that exist between different outcomes. By sharing the model outcomes in a plenary and interpreting the results together, the process can foster transparency, inclusivity, and accountability, allowing stakeholders to contribute to the development of distributional strategies that prioritize fairness and equity in resource allocation (McGookin et al., 2024).

***Within model logic*:** The all-affected principle of procedural justice can be captured within model logic by modelling public acceptance and opposition to projects by ensuring that all stakeholders, including those who may oppose projects, have a voice in decision-making processes. An exploration of what constitutes these perceptions of a just procedure / just outcome can be done using pre-workshop surveys and interviews, or cognitive maps as discussed in the previous section. The resulting justice perceptions can then be systematically incorporated into the model via model parameters, choice of input parameters, scenarios, choice of what outcomes will be measured or maximized for, the weights assigned to different parameters, relationship between model entities. Modelling and simulating the impact of different policy measures on their ability to fairly distribute access to clean, affordable energy to those who are disadvantaged (such as low-income groups, remote communities) would also be an operationalization of the all-affected principle. This is also an operationalization of substantive fairness in the way that the model explicitly explores policies that result in fairer distributions and policy outcomes for the vulnerable.

Participatory parity can be facilitated by capturing the heterogeneity of actors within the model, ensuring that the values and preferences of diverse actor groups are represented and given equal weight during the identification of preferences. This approach acknowledges the varied perspectives and interests of stakeholders and gives them equal opportunity and weight in the modeling process. Self-realization can be fostered by incorporating metrics in the model that result from exercises that elicit the individual's perception of what a just procedure or distribution means to them and ensuring that these perceptions are reflected in model choices. By integrating such metrics, the model has the potential to reflect the aspirations and priorities of the communities it seeks to serve.

Normative interpretations of distributive justice can be operationalized within model logic by integrating features that allow for explicit consideration of impacts across various dimensions such as space, time, and society. For example, to ensure that distributions improve availability and affordability to vulnerable members of society, the model should evaluate the distribution of costs, impacts, access, and availability across population, environment and impacts over time. By doing so, the model can evaluate equitable allocation of resources, considering factors such as income levels, geographical disparities, and temporal dynamics, to ensure fair access and affordability. Furthermore, inter-species and inter-generational justice can be promoted through the incorporation of metrics that measure the impact of alternatives and scenarios on different population groups, as well as on the environment and ecology, over time. This facilitates identification of distributional outcomes according to multiple principles of justice, considering the long-term consequences of decisions and their effects on both current and future generations, as well as on non-human species.

In Table 2, we outline possible ways in which different normative interpretations of justice tenets can be operationalized in the modelling process and as contained within model logic respectively. Formulating possible operationalizations as questions can prompt active reflection, encouraging modellers, users and stakeholders to deliberate upon and carefully consider whether and how justice principles are being incorporated into their processes and models. This is not meant to be a prescriptive or exhaustive list but is a first step aimed at assisting modelers and model-users in making explicit the diverse interpretations of justice principles present in real-life decision spaces. This can enable them to provide avenues through their models to support exploration of possibly non-dominant interpretations of justice so to holistically represent justice requirements of the decision-space within decision-support tools.

5. Conclusion

This paper highlights the different ways in which justice considerations are currently integrated into computational models supporting decision-making processes for the energy transition. There is a significant gap in the understanding of how justice is defined, interpreted, and implemented within models supporting energy transition decision-making. By adopting the three tenets of justice framework namely, procedural, recognition, and distributive justice, we have examined various computational modeling studies to elucidate the diverse interpretations and operationalizations of justice in the decision-making space. Our analysis shows that discussions of justice in the context of models and model-based decision-support cannot be separated from the design of effective participatory settings that stem from a careful evaluation of recognition justice and procedural justice requirements of the decision-space. We show that justice can operationalized in models at two levels: 1) within the modelling process: the way in which the model is conceptualized, designed, used, and interpreted and who is involved in this process; 2) within model logic: where justice concepts are implemented through model variables, in the choice of output metrics, in how the relationship between model variables are defined. Integrating justice into models is not akin to model-coupling or developing more metrics. It requires diverse normative interpretations present in the decision-space to be made explicit to both the individual and stakeholders as a group. It then requires an evaluation of how these justice principles can be incorporated into the modelling process and the decision-making process. This calls for the creation of participatory modelling frameworks that make

Table 2. Examples of how normative interpretations of justice tenets can be operationalized within model logic and within the modelling process.

Justice Tenet	Process Requirement	Model Requirement
Procedural	*All-affected principle*: Are all all-affected parties (or their representatives) invited to participate in the modelling process? *Transparency & Accountability*: Is the modelling process designed to receive and incorporate feedback from stakeholders at different stages in the modelling process? *Due-process:* Are privacy regulations followed during the deliberations, workshop sessions and data processing?	*All-affected principle:* Are public acceptance and opposition to projects modelled through direct stakeholder input, determining the model input parameters, scenarios, weights, and output metrics? Are justice considerations underlying public acceptance / opposition explored through surveys or interviews with stakeholders? Are model input parameters, scenarios, weights, and output metrics determined with stakeholder input? *Transparency & Due process:* Are different types of decision-making processes explored through models and their impacts at the institutional and individual/household levels analyzed? *Community empowerment:* Are model parameters (output and input) and relationships between variables and sub-models designed to reflect the priorities and social/political context of the locality?
Recognition	*Participatory parity:* Does the modelling process respect and account for differential requirements, identities and vulnerabilities resulting from the unique backgrounds of each actor/representative of a group present in the table? Is there an unbiased, neutral ombudsman appointed to address grievances concerning participation in the process? *Self-realization*: Does the modelling process provide avenues to incorporate non-dominant, non-western knowledge systems and worldviews in discussions during the modelling process for example, through cognitive maps, semi-structured interviews to elicit individual perceptions of what a just procedure or distribution means to them?	*Participatory parity:* Is the heterogeneity of actors captured in the model, giving equal weight to the values and preferences of diverse actor groups during the identification of preferences? *Self-realization:* Do choice of model metrics, relationships, uncertainty ranges and their values, result from both individual deliberations (through tools such as cognitive maps, semi-structured interviews) and group discussions, such that it allows for each individual and larger community to understand their motivations and perceptions of an energy justice solution?
Distributive	*Exploring multiple normative principles of distributive justice:* Are there avenues for exploring the impacts of different kinds of distribution of benefits and burdens together with stakeholders?	*Availability & Affordability:* Is the distribution of costs, impacts, access, and availability modelled across populations, environments, spatially, and temporally? *Inter-species and Inter-generational justice:* Are metrics included in the model that measure the impact of alternatives/scenarios on different population groups, the environment/ecology, over time?

justice central to the process and enable stakeholders to contribute meaningfully to the modeling process.

Our proposed conceptual framework is designed to ensure that normative uncertainties in the decision-space are made explicit, and diverse normative principles are adequately represented in both models and modeling processes. This framework aims to incorporate non-dominant worldviews or justice perceptions, potentially preventing existing inequalities from worsening and avoiding differential needs and vulnerabilities from being neglected or overlooked. By encouraging modelers and model-users to explicitly consider and integrate normative principles throughout the modeling process and model logic, we ensure that justice considerations are placed central to models used in energy transition planning. We start this conversation by providing initial recommendations on operationalizing normative justice principles in models. This paper opens avenues for further research in how justice is operationalized in models providing decision-support for energy transition. For instance, it is currently not clear if operationalization of procedural justice principles such as, inclusion of accountability mechanisms, setting up guidelines for model communication and transparency definitively improve perceptions of a just decision-making process and if the resulting policy outcomes will be perceived as just. Does including residents directly in the modelling process improve the perceptions of procedural justice compared to including only experts and institutional stakeholders? A systematic exploration of justice implications of choices made during the modelling process, will be valuable input into developing decision-support tools that better equipped to support decision-making for a just energy transition and is therefore an interesting avenue for further research.

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