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A Just Energy Transition is Not Just a Transition: Framing energy justice for a quantitative assessment

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Abstract

Considering the justice dimension in the energy transition context has become a key requirement for tackling current ecological and social issues. Due to this endeavour's complexity, quantitative energy models are helpful tools to inform decision-makers about policies' environmental and social consequences. However, most energy models have not been designed with this dimension firmly embedded. Some crucial questions arise: What is a just energy transition? Can we operationalise it? What does a quantitative model require to study the impacts of the energy transition on vulnerable people? What has already been done in this regard? We explore the conceptual background of energy justice to contribute to answering these questions by analysing how four quantifiable dimensions —energy access, energy security, energy democracy and energy poverty— contribute to addressing justice-related challenges of energy systems. Based on it, we highlight some strategies to assess energy justice through the energy cycle for a just energy transition. Within this context, we propose operationalising a just energy transition in long-term energy planning models with energy poverty at its core for developed countries' considering 41 essential parameters. We conclude by examining which of these parameters are included in energy planning models to assess the impact of decisions on vulnerable populations. The findings show that most models struggle to encompass these four dimensions of energy justice comprehensively. We conclude suggesting some operational criteria to advance quantitative analyses of justice dimensions in future developments, noting issues of using models within energy justice debates.

Keywords: Energy Justice, Energy poverty, Just Energy transition, Long-term energy planning, Optimisation models, Sustainability

1. Introduction

The world faces two daunting problems nowadays: an ecological crisis of unprecedented scale and vast economic inequalities from a social perspective. Current CO_2 concentrations severely affecting global climate are higher than at any time over at least the past two million years [1]. UNFCCC member states signed The Paris Agreement seeking to confront climate change and adapt to its inevitable effects [2]. In order to achieve this in a dignified way, an adaptation of the production and use of energy is required [3, 4]. Concurrently, 34 million people in Europe cannot afford the energy they need to guarantee decent and essential living standards [5]. Despite being unmistakable, tackling both challenges is not easy. Achieving an energy system that is environmentally sustainable and socially equitable is more relevant than ever before [6]. Amidst this complex interplay and the imperative for global energy transformation, the debate on just and equitable energy systems has taken centre stage. Many academics have recently contributed to a meaningful discussion around justice in energy systems, energy transitions, and sustainability. This has given rise to the concept of energy justice, defined as a *"global energy system that fairly disseminates both the benefits and costs of energy services and one that contributes to more representative and impartial energy decision-making"* [7, 8]. A dominant energy justice decision-making framework is based on eight principles to be promoted in the energy system: i) availability, ii) affordability, iii) due process, iv) transparency and accountability, v) sustainability, vi) intra and vii) inter-generational equity and viii) responsibility [7, 9]. Although significant progress has been made in characterising and quantifying energy justice, debates remain on its challenges, limitations, and conceptual foundations, inviting ongoing critical reflection [10–14].

The energy transition has also been discussed when associated with justice, and a just energy transition can be understood as a fair and equitable process of moving towards a post-carbon society [15]. Additionally, the challenges of a just energy transition are context-dependent and should be harmonised with the needs of each territory and its potentialities [16, 17]. Developing and least-developed countries focus more on guaranteeing energy access, mitigating energy poverty and protecting minorities affected by electrification processes, while in developed countries, the main focus of this document, the challenges remain in energy poverty and in employment impacts of decommissioning traditional energy sources. Although there are attempts to parameterise the impact on direct employment in the energy sector within long-term energy planning models [18], this study will focus primarily on analysing the other major dimension of the just energy transition for developed countries, namely energy poverty[1]. Hence, understanding the challenges and nature of a just energy transition, is key to avoid the perpetuation of social inequalities and to avoid worsening the living situation of future generations and the most vulnerable in particular.

While understanding energy justice is necessary to form a basis for fair decision-making on energy systems, scholars suggest it should also be operationalised into decision-making tools, notably computation models, to allow quantitative analysis and increase policy relevance [19]. Thus, policymakers will be able to make more informed decisions, analyse trade-offs of addressing challenges within established climate limits and to propose fair pathways that protect those in need during the transition, i.e., to propose a just energy transition. Despite recent efforts to propose metrics for energy justice [20], energy models so far have fallen short when including energy justice elements in their formulation [19, 21], so they provide short-sighted conclusions. This is one of the aspects that energy justice narratives miss the most [13, 19] and it is precisely the task where we intend to take a step forward. First, we set a context of energy justice that fits towards an operationalisation of the just energy transition in long-term energy planning models. Based on the eight principles outlined by Sovacool et al. [7], we propose their integration into energy modelling offering a quantifiable framework based on four core distinct, yet interrelated, dimensions: energy security [22–24], energy poverty [25, 26], energy democracy [27–30], and energy access [31–33] highlighting how each quantifiable dimension potentially contributes to quantifying justice in energy systems[2]. Second, we identify strategic actions that would make it possible, in principle, to advance the four dimensions of energy justice throughout the energy cycle while providing insights on what operationalisation endeavors should consider. From this point, we establish an approach to a just energy transition that allows, in the case of developed countries, to evaluate the effects on the most vulnerable populations of the energy-related decisions. In our analysis, energy poverty is the central axis of energy justice for developed countries. Then, we propose 41 essential parameters divided into eight categories for its operationalisation in decision-making tools. 26 representative energy models were analysed to detect to what extent they considered the proposed parameters. Thus, this paper explores a conceptual framework of a just energy transition and sets out a first step towards operationalising energy justice for a just energy transition in developed countries. To achieve this goal, and after the introduction, Section 2 establishes sustainability as the underlying rationale for the entire ecological-energy transition, representing the global challenge we face and lays a conceptual framework of a just energy transition illustrating how the energy justice approach may guide operationalising the just energy transition in quantitative long-term energy models. Section 3 establishes the general characteristics that energy models require to enable quantitative assessment of this energy justice framework in the long term. Section 4 proposes energy poverty as a central dimension of Energy Justice that captures the consequences of the energy transition on end-consumers and proposes the requirements for a quantitative model to study the effect of the energy transition on vulnerable people; it is set as a first step to the operationalisation of Energy Justice in decision making for developed countries. Section 5 studies existent energy models and shows how close they are to taking into account the proposed energy justice framework comprehensively and what remains to be done. Finally, conclusions are summarised in Section 6.

[1]The mechanisms to mitigate the negative employment impacts, e.g., re-skilling or employment in new sectors, goes beyond the scope of our analysis. However, the *employment status* will be considered later in Section 4.

[2]While energy security, poverty, and access can be quantified and directly integrated into energy models, energy democracy is included here to emphasise its critical role in shaping the decision-making process. The focus is on ensuring that democratic principles like participation and inclusivity are factored into assessments rather than being endogenously modelled.

2. Sustainable energy transition: A justice-based perspective

2.1. What do we understand for sustainable energy transition

The concept of sustainability.

Global ecological emergency and all its derivatives negatively impact social systems. These issues present technological and political challenges related to energy, a precondition of all goods, an essential life component such as air, water, and land [34]. Energy systems, the main drivers of the global economy and responsible for approximately 82% of the emissions reduction needed to reach net-zero goals by mid-century, have a significant influence in mitigating or exacerbating these issues [35, 36]. In response, 17 Sustainable Development Goals (SDGs) were established in pursuit of harmony and well-being for the planet and for present and subsequent generations [37]. For the European Commission (EC), energy supply and the need for an energy system that supports climate change mitigation and seeks non-detrimental impacts on society, especially vulnerable populations, is also a priority [38].

The energy transition initially emerged as a strategy that sought to address these issues, seeking mitigation of the effects of energy systems on the planet by reducing fossil fuel dependency mainly focused on techno-economic aspects [39–42]. It is a multidimensional challenge encompassing economic, environmental and social notions at intragenerational and intergenerational levels [43]. It is no coincidence that the energy transition is a response to this double socio-ecological challenge, which is none other than the challenge of sustainability [44], a key element to promote in energy sytems. Sustainable development[3], has gained increasing attention in recent years

[3]In this paper, the terms 'sustainability' and 'sustainable development' are employed interchangeably for ease of understanding. However, they convey separate concepts. Sustainability pertains to the long-term resilience of a system, encompassing environmental, social, and economic aspects. In contrast, sustainable development applies this principle to a specific objective, namely human development.

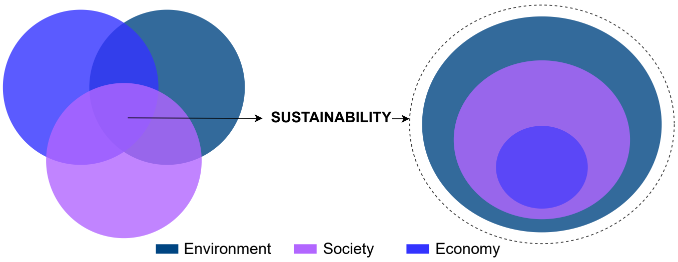

Fig. 1. Integrated approaches to sustainability [50, 51]

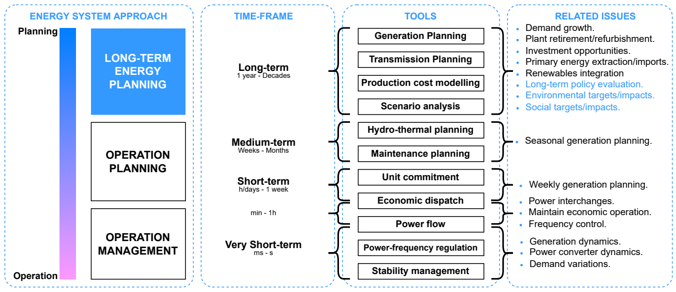

Fig. 2. Time frames, issues and tools for long-term energy system models [57].

as the global community grapples with the imperative to meet the needs of present and future generations while staying within the limits of the planet's ecological systems [45, 46]. Central to this challenge is balancing economic and societal development with environmental sustainability. A task that requires a holistic and, also, long-term perspective [44, 47–49].

Operationalising sustainability

Figure 1 shows two traditional integrated approaches to sustainability that might provide a conceptual framework in this operationalisation task.

We consider that the hierarchical approach to sustainability in the right-hand side of Figure 1 fits for addressing it since it recognises the interchanges between all three dimensions and that sustainability problems are influenced by the hierarchical limitations of diverse social, economic, and political systems operating at different scales. At the same time, it proposes boundaries for each dimension, establishing the main priority for the environmental dimension over the social and economic ones and then putting social boundaries for the economic aspects. While the hierarchical structure of the nested approach acknowledges the inter-dependencies among the economic, environmental, and social dimensions, it falls short of explicitly incorporating justice considerations. This demands a deeper integration of justice principles into the nested approach.

This approach is consistent with visions such as the one proposed by Raworth et al. [52], where a social foundation aims to ensure that no one's basic needs are unmet, and an ecological ceiling aiming to prevent humanity from causing irreversible harm to the planet's life-supporting systems. Authors in [53] went from providing a quantified safe space within planet boundaries to establishing that the interconnectedness between the stability and resilience of the Earth system and the well-being of humanity is indivisible and inextricable [54]. Gupta et al. [55] illustrate the necessity of modifying boundaries to mitigate detrimental impacts, enhance inclusivity, and confront inequality, all to safeguard a secure and equitable future for human beings, biodiversity, and the Earth system. In line with this, authors in [56] have identified three general aspects, at both intra and intergenerational time-frames, that are in-depth required for a sustainable energy transition: 1) The level of well-being should not decline, 2) critical socio-environmental boundaries should be respected, and 3) fair distribution must be guaranteed. From the energy system perspective, these aspects can be operationalised in quantitative energy models since they play an important role in evaluating the future performance, composition, and impact of energy systems. Figure 2 shows different approaches to energy system modelling based on the time-frame and the related issues they tend to address.

The long-term energy planning purpose is to find the optimal energy cycle composition, which refers to all energy processes, from the set of primary resources to the energy conversion and supply technologies to meet the energy demand in a desirable way. It can be addressed by optimisation, accounting, econometric or hybrid techniques using top-down or bottom-up approaches with different levels of foresight [58, 59]. While modelling this three aspects could be undoubtedly a step forward in incorporating justice criteria into operational approaches of a transition to sustainability, it is not enough. Addressing distributional effects is pivotal to the equitable dissemination of transition benefits and costs across diverse societal segments and amplifies the efficacy and longevity of energy transition policies, concurrently fostering broader viability and acceptance of the overarching agenda [60]. Yet, ensuring inter- and intra-generational justice goes beyond considering only distributional aspects in long-term energy modelling. In this regard, for our inquiry into energy justice, we employ a contextualisation of justice as a qualified horizon to frame our reflection on energy justice from a quantitative perspective.

2.2. *Binding energy and justice*

2.2.1. *Approaching Justice in the energy transition.*

Ranging from justice as fairness to frameworks emphasising the flourishing of individuals to lead lives imbued with personal value or essential capabilities—such as health, education, energy, and political participation— to be promoted, justice concepts are diverse and multifaceted [61–63]. The contemporary debate revolves around what dimensions and from what foundations we can speak of justice and how the various spheres of distribution and redistribution develop.

Just as authors in [7] proposed cosmopolitan justice as a contextualisation for their approach, we present the recognitional, procedural, distributional, and restorative dimensions of justice not as a definitive stance on which justice principles are normatively accepted, but rather as a plausible framework for contextualizing the issue of justice [61, 64–66]; a framework that has been applied across various fields: territorial inequality, food, environmental justice, education, health and energy [67–69], and that is productive for thinking about energy justice (as will be seen later in Table 1). Recognition as justice embodies representation and acknowledgement of differences in reaching a just society. Procedural justice pertains to a just and equitable process that guarantees and supervises the meaningful involvement of all stakeholders. Distributive justice aims for a fair and even distribution of resources, benefits, opportunities, and burdens while identifying any imbalanced distribution of responsibilities [70]. The restorative dimension of justice pertains to facilitating the healing of the harm that has been done under a particular situation, addressing the root causes to benefit all parties affected, ensuring compensation for damages and losses and forming preventive and forward-looking actions associated with difficulty in applying justice [14, 71].

2.2.2. The relation between energy and justice

It is easy to see how energy and its management challenges are related to the challenges of justice [8, 14]. However, to promote a just energy system, it is crucial to develop strategies that incorporate a justice perspective into energy policies throughout it. Likewise, quantitative justice perspectives need to be included in long-term energy models to evaluate a just energy transition[4]. This entails adopting holistic quantitative approaches that integrate practical justice considerations into decision-making processes, ensuring that energy systems are designed and implemented to uphold principles of equity, inclusivity, and fairness for all stakeholders. Thus, analysing the implications of justice in the energy system is necessary for advancing the justice-based requirements a just energy system should meet. In the subsequent lines, we examine how these justice dimensions manifest in each stage of the energy system.

Recognitional justice in the energy system

Addressing recognitional justice towards a just energy transition means acknowledging that big portions of society do not benefit from the actual energy system, and many do not fulfil the requirements for a dignified living, i.e., the transition departs from a point where there are people behind. Additionally, there are portions of the population whose employment will be affected negatively that should be protected. For recognitional justice, ensuring that all actors are recognised as relevant, protected and represented in the energy process and the decision-making that shapes it, is essential. In processes geographically isolated, such as extraction, production, decommissioning, and waste management, not recognising different social structures can degrade and despised portions of society [72], which will reproduce geographical inequalities [73]. The living conditions of some communities are different, and certain vulnerable areas are not identified as requiring assistance [74, 75].

Procedural justice in the energy system

Procedural justice ensures that all communities and individuals are considered during the energy transition, establishing fair and inclusive decision-making, access to information and access to justice mechanisms that empower stakeholders to participate in shaping the future of energy. At the supply and consumption stages, decision-making should be transparent and equally serve society to protect consumers and guarantee their engagement to create strategies that minimise inequality [76] and guarantee accessibility to affordable and reliable energy services. This entails moving beyond a profit-driven economic model, e.g., to the Triple Bottom Line or the Shared Value, for balancing economic prosperity with social considerations for low but stable and equitable price setting. However, a detailed analysis of how these economic approaches could facilitate a just energy transition is the subject of future work [9, 77]. It is imperative to set up procedural mechanisms that regulate the relationships between industry, government, and communities engaged in energy processes, considering power dynamics and disparities ingrained in systemic inequalities [78–81]. Addressing the transition from a procedural justice perspective could allow a more democratic, consistent, inclusive, and legitimate process reflecting the needs and aspirations of all stakeholders. [72, 79, 82, 83].

Distributive justice in the energy system

Distributive justice ensures that the benefits and hardships associated with the transition are shared equitably among all stakeholders [60, 84, 85]. It emphasises the fair distribution of resources, opportunities, and outcomes related to energy production, consumption, and the overall energy system [86]. The influence of distributive justice for extractive, centralised energy production, decommissioning and waste management processes is complex as they are technically and geographically constrained. However, as regularly occurring in areas isolated from big consumption centres, these processes require distributive dynamics to equate benefits to affected local communities while protecting the labour sector [79]. There is a need to ensure that everyone has access to the energy they need safely, securely and at a fair energy price consistent with their particular conditions to guarantee a decent living. Nonetheless, when assessing energy consumption, this is where most inequalities appear, or at least they are more evident. Notions of distributional justice related to energy consumption are usually framed in terms of affordability [76]. Affordability issues reflect inequalities at various levels, such as household income, high energy prices, or even housing quality, which directly impact health or education [87].

Restorative justice in the energy system

Restorative justice emerges as a dimension that directly addresses the segments of society neglected by the existing energy system, particularly those left behind towards a new energy landscape. It emphasises the need to repair and

[4]Energy justice frameworks are diverse and do not universally adhere to a single theory of justice, which makes quantifying justice challenging. While the exact measurement of justice is complex, models can incorporate metrics that approximate core characteristics that might contribute to just outcomes. These metrics, though they act as proxies rather than definitive measures, are grounded in established energy justice dimensions.

restore the well-being, dignity, and rights of individuals and communities historically suffering from energy-related injustices. Restorative justice also highlights the importance of reparations and redress for past harms in the extractive, production, decommissioning and waste management stages [71] by including compensation, resource allocation and support for community-led initiatives. Similarly, in the consumption stage, the restorative dimension seeks to mitigate the effects already produced on the most vulnerable consumers affected by the direction of decision-making and who do not receive the benefits of these decisions and do not have access to affordable and clean energy services [73].

Analysing the dimensions of justice in the energy cycle reveals many challenges towards achieving a just energy system, i.e., energy should be available, accessible, affordable, and reliable while considering due process, environmental sustainability, intra and inter-generational equity, representability, resiliency, and participation in decision-making. In the next section, we delve deeper into what literature describes as energy justice, which we consider allows a more technical vision of justice within the energy transition. We discuss its theoretical underpinnings, practical applications, its limitations and how it serves as a guiding principle for the transformation towards a more equitable and inclusive energy system.

2.2.3. *Energy justice: an operationalisable vision.*

This approach to energy justice can be operationalised into decision-making tools that can aid energy planners with metrics to guide the design, implementation, evaluation and assessment of energy-related processes, encompassing the complexities of procedures, distribution, recognition, and restoration as foundational pillars [9, 20]. It can provide information to address societal disparities, emphasising the evaluation and mitigation of environmental impacts and facilitating empowerment and meaningful choices in energy consumption and production. In doing so, energy justice converges towards an energy landscape characterised by accessibility, affordability, security, and democratic participation, thereby advancing a more equitable and sustainable energy future.

2.2.4. *Energy justice quantifiable aproach*

Building on what authors in [7] proposed, we coherently synthesise the eight applied principles of energy justice in four quantifiable dimensions, i.e., energy access, energy poverty, energy democracy and energy security. The first dimension addresses the situation where people lack access to a minimum level of safe and modern energy and aligns with intragenerational equity vi), ensuring fair and equitable access to energy services for all. This is a very sensitive problem for isolated populations in Latin America and for almost half of the sub-Saharan African population [88]. The second dimension, energy poverty[5], appears as an issue where households cannot meet their primary energy needs due to a combination of at least three factors, i.e., high energy prices, low-income, and low energy efficiency. Energy poverty analyses focus on seeking affordability ii) and reducing financial burdens for consumers, particularly for vulnerable populations. The challenges posed by energy poverty are compatible for both developed and less developed countries, but in the case of the latter, they interact with energy access issues in different ways. Despite there being no consensus on the definition of either energy access or energy poverty, it is important to note that both definitions bring different quantitative metrics, and since we intend to provide an energy justice operationalisable approach for long-term energy planning, their separation coherently contributes to the required contextualisation of a just energy transition[6]. Thirdly, energy democracy[7] incorporates due process iii), transparency and accountability iv), and responsibility viii), fostering inclusive and fair participation in energy decision-making, including the idea that the communities should participate in shaping their energy future since not all communities have the exact needs [27, 89, 90]. Finally, energy security dimension covers areas associated with energy availability i), infrastructure and service reliability, stability, resiliency, energy pricing and energy efficiency [22, 23]. Considering our analysis, this dimension has an important nuance. It is a techno-economic macro-vision of the energy system whose justice-related consequences after maintaining (or not) energy available affect other dimensions [91]. For instance, whether gas imports are reduced or increased is an issue directly associated with energy justice , but the effects that price variations will have on consumers , as a reaction, are associated with energy poverty. Likewise, the characteristics associated with a reliable and environmentally benign energy service are more associated with energy access. In our approach, sustainability v) represents the global challenge we face, justifying the need for transformation. One essential requirement for this transition to be genuinely sustainable is that it must also be just (see Section 2.1) to guarantee inter-generational equity vii). Thus, in our proposal, sustainability and inter-generational equity are embedded in all four dimensions and understood as the starting point of energy justice rather than its endpoint.

This non-normative proposal is designed to support a structured approach without prescribing specific policies. While it may not capture the full complexity of energy justice, we do believe that these dimensions address core principles of energy justice relevant to long-term energy modelling and decision-making in a just energy transition.

This energy justice approach is diverse and multifaceted, founded on procedural, recognitional, distributive, and restorative justice while consolidating eight principles to be promoted

[5] Although transport poverty definition is sometimes associated to energy poverty, it measures a different dimension of poverty. It includes elements associated with affordability and aspects associated with the accessibility or non-availability of transport services, private or public. However, the consideration of all expenditures, including transport expenditures, is necessary for measuring energy poverty.

[6] There are long-term energy models designed for considering metrics associated with energy access analysis and other modelling approaches that include energy poverty-related issues.

[7] We do not intend to reduce the broad theory surrounding energy democracy but we intend to include it in a practical way in the link between energy justice and long-term energy models.

in energy systems [7, 92, 93]. Then, addressing energy justice from a quantifiable perspective should allow us to understand and respond to energy-related injustices effectively. Table 1 presents a breakdown of energy justice quantifiable dimensions in an effort to reflect the justice aspects they tend to address, establish their scope limits and reveal potential tensions in the context of an energy transition.

It is considerable here that the overarching goals of distributive justice also underline the need to address historical inequalities, engage marginalised communities and rectify previous damages to ensure a truly equitable and sustainable energy transition, i.e., applying restorative justice through just procedures. This means recognising that decision-making can affect people in very different ways and vulnerable portions of society do not deserve equal but special treatment. In the case of energy poverty, although mitigation measures rectify unbalanced distributional impacts, they can even inadvertently perpetuate existing inequalities, potentially creating an illusion of equality since they do not contribute to restorative justice [97]. Likewise, this holistic perspective allows to understand that energy access constitutes only a pre-condition for a just energy system, and it should be followed by policies to reduce all forms of energy poverty [24, 93, 94, 103] (this will be analysed further in Section 4). Thus, improving energy access is not only related to restorative issues but also is directly related to recognising extra necessities of marginalised societies, establishing a link between energy access and energy poverty. In developed countries, the mere assurance of access, security, or democratic participation in the energy realm falls short if energy affordability remains unattained. Energy poverty is identified as the linchpin that connects and amplifies the impacts of other justice dimensions for future energy scenarios. While addressing injustices surrounding energy access, energy security, and energy democracy is mandatory, a substantial emphasis should be placed on tackling energy poverty.

2.2.5. *The just energy transition*

Making the energy system more just today and ensuring inter generational equity is a critical challenge for moving towards a post-carbon society [72]. This just energy transition must simultaneously respond to climate and environmental imperatives, unfold at a pace that matches the urgency of the challenges, and meticulously consider its impacts on society. Consequently, integrating the multiple dimensions of energy justice within decision-making processes is essential to achieve an equitable energy transition. This requires that these dimensions not only be operationalised but also quantified in ways that allow for their endogenous representation within long-term energy models. In Table 2, we highlight some strategic actions within the four dimension framework of energy justice presented above that could be assessed at every stage in the energy cycle to contribute to a just energy transition. In this way, under the energy justice definition, we try to show how the energy transition assesses the impact of decision-making on vulnerable people and the considerations that should be taken into account by long-term energy models.

It becomes evident that the different dimensions are interrelated. First, mechanisms that guarantee access should also guarantee a reliable and resilient service. But it is also required to integrate affordability options to assure essential energy consumption necessary to ensure decent living conditions. Secondly, an uninterrupted and reliable energy service is not enough for essential and equal energy consumption unless it is affordable. Moreover, strategies enhancing energy security, from diversified energy mixes to stable pricing in extraction, production, and consumption stages, are intertwined with alleviating energy poverty. Third, for a just energy transition, energy security mechanisms fall short if they only look for energy availability during a crisis, improving the energy mix or establishing reliable services. They should also contribute to minimising the uneven impacts on society by maintaining the energy service and allowing essential energy consumption. Fourth, energy democracy implies that decision-making procedures contemplate all stakeholders' consequences, including environmental ones. At the same time, energy poverty collects the characteristics associated with not satisfying essential consumer needs despite having energy access. Also, addressing each of these dimensions, can result in trade-offs. Policies that prioritise energy security through diversification of energy sources may lead to higher costs, potentially compromising affordability for vulnerable populations. Similarly, efforts to expand energy access might involve infrastructure projects that could conflict with local communities' democratic rights and environmental concerns. These trade-offs highlight the complex balance needed when pursuing a just energy transition. Further research is essential to better understand and navigate these interdependencies.

3. Quantitative long-term models and the Just Energy Transition

Before establishing the general characteristics that energy models require to enable quantitative assessment of energy justice in the long term, we consider it relevant to analyse how the energy transitions are planned and why energy models play a critical role in their planning.

3.1. *Planning the energy transition*

Energy transitions are envisaged as long-term strategies that serve as a roadmap setting out clear, ambitious and achievable energy-related objectives. These strategies include a comprehensive set of policies and regulations to incentivise, e.g., renewable energy deployment and support the clean energy transition. However, the decisions that are made to produce this package of strategies should be evidence-based. Quantitative modelling provides a powerful tool for stakeholders to make more informed decisions. However, energy models do not always endogenously include all the necessary energy justice features to enable a just energy transition to be evaluated. The example of Spain's national energy and climate plan is clear [113]. For the design of this plan, all decision-making bodies relied on the evidence provided by TIMES, which is a well-known

Table 1
Energy justice dimensional challenges in the energy transition context. Based on [72, 74, 101, 102]

JUSTICE	ENERGY JUSTICE*			
	Energy access [31–33, 94, 95]	**Energy poverty[96–99]**	**Energy democracy** [27, 89]**	**Energy security*** **
Recognition [75, 100]	Recognise different communities' particular necessities and shortcomings, their allocation and cultural traditions while guaranteeing affordable energy availability within a reliable energy infrastructure considering its environmental impacts.	Awareness of all forms of energy poverty and vulnerability to energy prices for recognising, without stigmatisation, the needs, preferences, and living conditions in different geographies of vulnerable and energy-poor households to guarantee affordable energy service.	Recognise the under-representation of the community in community-based energy projects, energy services, energy policy issues and decision-making. Recognising the employment implications of decommissioning power plants.	—
Procedural [83]	Promote accountability, community benefits agreements, and oversight in implementing energy policies and programs to establish credible institutions and viable business models that can implement and enforce regulations with autonomy to allow generalise energy access and mitigate energy disruptions with all stakeholders' participation.	Foster partnerships between community organisations, government agencies, and energy stakeholders to address energy poverty. Implement mechanisms to hold energy stakeholders accountable. Devolve decision-making authority to local levels to establish affordable and equitable energy pricing.	Empower communities with local capacity, authority, employment opportunities and ability to transparently participate in consensus and unbiased-based decision-making and the knowledge and skills to oversee energy governance. Provide communities with principles that guide policy and action towards a just and democratic energy system.	—
Distributive [76, 86]	Distribute equally through a resilient energy infrastructure, reliable, accessible, affordable and efficient energy services, technologies and capacities. Propose energy management models equitably and fairly to establish energy availability at society's overall disposition for present and future generations.	Address distributional burdens of increases in energy prices, establish progressive pricing mechanisms, equitable low rates for essential energy services, apply targeted subsidies and distribute equitably outcomes in the form of benefits and services to different target groups. Guarantee equal access to strategies to mitigate energy poverty.	Allow ownership of energy projects, facilitate the establishment of energy cooperatives and decentralise decision-making while creating value through equitable engagements with energy systems across all communities and, for all, outweighs the costs, burdens, and risks that energy systems impose.	—
Restorative [71, 73]	Prioritise reinvestment of resources in microgrids or decentralised energy systems for historically disadvantaged communities in terms of energy access improving reliability and resilience. Energy policies consider the specific needs and circumstances of vulnerable and marginalised populations, aiming to bridge existing disparities such as lack of access to energy.	Rectify historical energy poverty by allocating resources and investments to improve energy efficiency, prioritising communities disproportionately affected. Include targeted funding, household retrofitting, energy efficiency programs, and innovative financing models that prioritise the needs of affected populations. Lifeline tariffs, or innovative pricing models, incentivise energy conservation and reduce the financial burden on harmed people.	Expand opportunities for historically marginalised communities to participate in energy governance and in decision-making processes that affect them. Rectify negative employment impacts of the energy transition.	—

* Following the definition of energy justice, all the mechanisms named in this table, which serve as its elementary pillars, are encapsulated within environmental justice, i.e. care for the environment, the health of communities and the environmental impacts of such strategies are taken into account.
** The approaches listed do not aim to establish degrees of democracy definitively or to infer that centralised systems are not democratic. Instead, they present options that challenge the dominance of traditional energy consumption, centralised decision-making and production methods, contributing to a more diversified and inclusive energy landscape.
*** Energy security is a fundamental pillar for energy justice. However, this dimension is a dimension that focuses on operational techno-economic aspects of the energy system to ensure quality and continuity of service. Then, its impacts at the social level are captured in other dimensions.

and robust long-term energy model. However, the energy-based notions of justice are considered exogenously in TIMES. This could result in biased decision-making and increase the risk of overlooking disparities in access to energy resources, affordability issues, and the equitable distribution of benefits and burdens associated with the energy transition. Then, incorporating endogenously integrated data related to energy justice into modelling practices is essential to properly address a just energy transition.

3.2. Optimisation-based long-term energy models.

Energy models for long-term planning are quantitative and techno-economic tools that, usually by means of mathematical optimisation[8], seek to find the future optimal configuration and performance of the energy system that covers the estimated demand and achieves a given objective while complying with previously established constraints. Implicit objectives include cost minimisation of, e.g., primary energy investment, energy conversion, energy system operating costs, energy generation, minimisation of GHG emissions, or maximisation of net social benefit. In terms of restrictions, they are usually hard constraints that indicate, for example, the maximum investment that can be made in generation technology, the maximum allowable amount of GHG in a particular energy sector, e.g., energy production, or the minimum amount of investment in the residential sector that should be allocated every year for vulnerable households. However, in the modelling exercise, it could be indicated that, in a given situation, there are restrictions that could be breached. These are called soft constraints. Depending on the objective of the analysis of a long-term energy model, they can be designed considering different aspects. To analyse a Just Energy Transition is no exception.

3.3. Modelling characteristics for a Just Energy Transition.

Energy system models can be categorised using a wide number of alternative criteria [58, 59, 114]. Focusing on a Just Energy Transition, we consider five general aspects that long-term optimisation-based energy models should focus on: (i) goal, (ii) analytical structure, (iii) timescale, (iv) endogenisation degree, and (v) spatial dimension [115, 116].

In regard to the (i) goal, long-term energy models should allow the determination of the conditions for a just energy fu-

[8]There are also econometrics, macro-economics, economic equilibrium, and simulation methodologies. See [58] for a full review of types of energy models.

Table 2
Justice dimensions approaches to the energy transition activities from the social perspective.

Energy Justice	ENERGY CYCLE STAGE				
	Extraction and Imports	**Production**	**Operation and Supply***	**Consumption**	**Decomissioning and Waste management****
Energy access [31, 104]	N/A	Invest in electric power generation infrastructure, including on-grid and off-grid solutions like microgrids, and prioritise long-term investments in electrification.	Invest in transmission and distribution infrastructures to enhance access to new and clean energy technologies. Establish credible institutions and viable business models that can implement and enforce regulations with autonomy.	Electrification requires subsidies and appropriate pricing structures to ensure sufficient revenue collection for the system's cash flow requirements and essential energy consumption. Good customer support, maintenance, accurate billing, and simple payment processes are necessary to maintain positive customer relationships.	N/A
Energy Poverty [96, 105–109]	Employment generation, tax income for energy assistance initiatives targeting disadvantaged households, and community-benefit agreements.	Allocate investments towards both centralised and decentralised renewable energy technologies directed to vulnerable households to encourage competition and diversity in the energy market to foster innovation and potentially lead to more affordable energy options.	Promote long-term contracts, support community-owned energy projects, implement interventions during electricity price crises, develop strategies for efficient supplier risk management, implement flexibility support schemes and capacity remuneration mechanisms. Invest in local energy infrastructure, promote positive energy districts, and guarantee a minimum essential energy supply providing disconnection protection.	Enhance energy efficiency in buildings and appliances, offer financial support such as subsidies or grants to encourage rehabilitation. Implement mechanisms to avoid over-consumption, provide energy management education, and promote community energy projects. Enable pricing strategies for vulnerable households and allow interventions during energy or climate crises.	The economic costs of decommissioning, which are sure to be significant and will increase as more assets reach the end of their life, should be distributed equally between stakeholders. Protect local employment and income when decommissioning.
Energy democracy*** [28–31, 110]	Educate and increase community awareness to promote understanding of the appropriate human-natural resource relationship and the importance of ecological sustainability and allow their participation in extraction-related decision-making.	Encourage decentralisation, social and collective ownership and energy production while ensuring decarbonisation is accompanied by social energy control. Community engagement is critical for successful electrification projects.	Empower local communities to make energy decisions and involve citizens in energy ownership, distribution, and usage. Enable affected communities to participate in selecting the energy sources and distribution entities.	Ensure energy affordability, provide access to energy-efficient products and management technologies, facilitate access to energy information and actively involve community members in information campaigns.	Promote community-led solutions to ensure that decommissioning and waste management processes are both environmentally sustainable and socially just while involving a broad range of stakeholders in decision-making processes.
Energy security [22, 23, 111, 112]	Ensure protection against harmful energy import disruptions by improving the energy mix diversity with a balanced supply of various energy types.	Improve energy production efficiency and establish strong energy trade partnerships with neighbouring countries and regions to enhance energy resource diversification, promote distributed energy resources, and invest in improving energy transformation facilities to guarantee an uninterrupted and safe service.	Improve technological safety of transmission and distribution infrastructure, increase new technologies such as energy storage capacity, upgrade energy equipment performance, including users' connections to the grid, and alter consumer behaviour to reduce energy price exposure and dependency on energy imports. Design resilient grids to ensure the survival of the electricity system during an extreme weather event and guarantee continuity of service and economic activity.	Ensure reliable energy services to maintain acceptable social and economic welfare and minimise price volatility for present and future generations. Resilient Housing Standards, integration of backup power systems and energy storage accessibility.	Provide alternative energy sources and ensure that communities are not negatively affected by the decommissioning process. Plan the decommissioning process to minimise disruptions to the energy supply and improve the resilience of the system transitioning from conventional to renewable sources.

* Includes infrastructure investments
** Although associated with decreased system capacity, decommissioning is often paid for in energy prices.
*** Although energy democracy features can be identified throughout the energy cycle, stakeholders' decisions could be considered in further assessing a proposed just energy transition scenario. In this way, the proposal of a transitional pathway can be democratically decided.

ture, identifying drivers and barriers while defining the steps to achieve it. In this sense, seeking the shifts to define a just energy transition, backcasting serves as an alternative to other approaches that use, e.g., past observations to extrapolate and predict the future, which is seen as a preservation of the past and present tendencies. (ii) Analytical structures, top-down or bottom-up, are principally differentiated by the level of disaggregation. Considering the components and the interconnections of the energy sector in a disaggregated way enables the study of the end-use of energy in great detail in a particular subsector, e.g., residential. This is a bottom-up analytical approach, that contributes to including energy justice considerations in a long-term energy model. (iii) Regarding the timescale, under a static approach, an energy model optimises for a single year in the future, assuming that this year is representative of the rest of the previous years in the time window. Instead, dynamic models may be used for longer time horizons as the final year of analysis considers decisions taken in the previous years. This is due to the multiple time steps that the optimisation time window integrates. This will allow the problems to be tracked step-by-step and include restrictions for each one, e.g., coal power generation will no longer be considered after a certain year. Perfect foresight dynamic models assume the perfect knowledge of future events at the entire time window, while limited foresight models optimise for each time step, with information limitations about the future system evolution. Dynamic approaches may allow an understanding of the interactions between energy, economy, environment, and society and how these interactions affect energy justice over time. The (iv) endogenisation degree refers to the inclusion of the parameters directly within the energy model. For a just energy transition, a high degree of endogeneity of energy justice parameters will allow for evidence of how energy justice is influenced by the decisions and outcomes generated within the model. Including them exogenously may result in less accurate estimates and an inability to model how energy policies can influence energy justice and vice versa. Considering the (v) spatial dimension is also relevant for a long-term energy model. They can go from global or international regions, e.g., the EU, to a national-level analysis. Since energy decision-making rests with national or sub-national governments, and each country has diverse socio-economic, political and energy contexts, as well as different priorities in terms of energy justice, we consider that a long-term energy model should assess the just energy transition at a national level. Furthermore, the modelling efforts for just energy transition depend on the energy justice priorities of each territory.

3.4. Assessing energy justice dimensions in long-term energy models

To assess the *energy access* dimension, modelling approaches should integrate information to identify the most cost-effective ways to expand access to modern energy services. To do this, they should disaggregate the data by population and geography to characterise the potential customer types and consumption profiles to define the current electrification status of buildings. Estimating the energy demand is crucial for building the right systems to serve users, accurately incorporate more generation technologies and enable better resource allocation.

In the case of *energy poverty*, long-term energy models should consider a disaggregation of the residential sector, especially of the most vulnerable households, according to income, building type, household composition, and energy efficiency. In this sense, the integration of the energy expenditures of each user profile on different energy services is key. Additionally, the geographical disaggregation of energy demand will allow for the inclusion of the different needs of final consumers depending on the climatic circumstances. Integrate the price of energy for end-consumers to consider expenditures on different energy services. These energy models should consider covering the estimated real demand and the estimated demand required to cover basic needs.

Unlike energy poverty and energy access, which are analysed in different ways and with different considerations by energy models, *energy security* is a cross-cutting issue that seeks to guarantee the continuity of service regardless of climatic or political conditions that hinder it. To be considered at a general level, energy models must consider imported and domestically sourced primary energy as well as ensure that the energy balance is met in all sectors (transport, industrial, residential, commercial and services) while fulfilling GHG emissions constraints. This is considering new technologies for energy generation and the decommissioning of traditional ones as well as the costs of operation, conversion and transport of energy.

As for the link between *energy democracy* and long-term energy models, the latter should gather the interests of all stakeholders in the limits placed on strong and weak constraints as well as on the objective function that the energy model seeks to fulfil. So, this dimension is included in a practical way in the ex-ante modelling exercise in how these are designed and validated, but, in addition, it should be considered in the ex-post analysis of results to evaluate and the re-calibrate it.

3.5. Challenges and limitations of modelling energy justice.

In considering energy justice in long-term energy models, several challenges arise, particularly concerning the limitations of translating justice principles into quantitative measures. Energy justice frameworks lack a single, universally accepted theory of justice, which introduces potential disanalogies between chosen parameters and the broader, sometimes competing, theories of justice. This raises tensions, as modelling justice may rely on measurable proxies, such as energy poverty in this case. This do not fully capture the philosophical depth of justice debates. Then, models risk oversimplifying complex justice issues, leading to potentially reductive interpretations. This approximation underscores the importance of cautious interpretation, acknowledging that such models offer valuable insights yet do not encompass the full depth of energy justice debates

4. Operationalising energy poverty for a Just Energy Transition in Developed countries

Standing on the previous conceptual ground, this section presents energy poverty as a central energy justice priority for developed countries. In developing countries, the issue of energy access is also followed by affordability challenges. The case for developed countries is different. In developed countries, energy access is assured and energy security levels are robust enough to guarantee the continuity of the energy service. However, energy security depends on the availability of different primary resources. This leads to volatility in final energy prices. Such volatility disproportionately affects the well-being of the most vulnerable members of society. Energy poverty highlights the urgent need to address the complex interplay between energy security, affordability, and social well-being. Recognising, addressing, and operationalising it is a sine-qua-non condition for advancing a Just Energy Transition in developed countries[9]. Thus, comprehensively understanding energy poverty, its metrics, and how a just energy transition can include its effects is elemental.

4.1. Deepening on Energy Poverty

The European Energy Efficiency Directive establishes that energy poverty means "*a household's lack of access to essential energy services, where such services provide basic levels and decent standards of living and health, including adequate heating, hot water, cooling, lighting, and energy to power appliances in the relevant national context, existing national social policy and other relevant national policies, caused by a*

[9] Affordability is an issue also related to low-income countries. Thus, although our approach stems from an approach for developed countries, it is completely valid to take into account affordability, with the necessary nuances, in developing countries.

combination of factors, including at least non-affordability, insufficient disposable income, high energy expenditure and poor energy efficiency of homes". In developed countries, economic factors are the primary drivers of energy poverty [117], while in developing countries, other restrictions, e.g. prolonged power outages or low-quality infrastructure, can also contribute to the problem. Energy poverty has emerged as a significant energy-related societal challenge with heavy consequences in health, education, economic opportunities, and generalised well-being. Mitigating these problems is difficult, especially given the urgency to meet climate objectives. Therefore, addressing energy poverty in a just energy transition scenario is essential to develop regulatory strategies to deal with these problems while considering sustainability and climate objectives.

4.2. Integrally measuring energy poverty

The task of measuring energy poverty is not simple. It manifests in many forms depending on the type of consumer, the region, the energy consumed, and even interpretations of their particular situation. Therefore, no single metric measures energy poverty at a general level. To provide a better understanding of the variety of approaches, one way to classify energy poverty metrics is to distinguish them into two main categories of indicators: subjective and objective [118, 119]. Subjective indicators are focused on qualitative data collected through surveys, while objective indicators rely on quantitative data obtained from households. In the context of objective indicators, the most significant ones refer to household income and expenditure. Among these, a further categorisation can be made based on the energy poverty aspect they aim to measure, namely whether it pertains to disproportionate expenditure or under-spending. Normally, many discrepancies often arise when measuring energy poverty depending on the approach used. Regularly qualitative indicators identify more people suffering from energy poverty than quantitative ones, but there are quantitative indicators, e.g., the 2M[10] indicator that has a very similar or higher incidence when compared to qualitative indicators, such as inadequate temperature. Then, to assess these discrepancies it is necessary to contrast the results to conclude and propose measures to mitigate the effects that each indicator considers. Comprehensive literature reviews regarding the metrics of energy poverty, their pros, cons, and policy implications can be consulted at [119–121]. The calculation of energy poverty indicators in the evaluation of a just energy transition using a long-term energy planning approach requires an ex-post analysis based on the results obtained using the modelling tool, i.e., the energy flows that show how the energy services are met at the residential level. Then, the indicators that this calculation allows to obtain are necessarily quantitative. The 2M indicator, despite being easy to calculate, is very sensitive to energy prices; e.g., it might underestimate energy poverty when prices are low. Moreover, it goes through many other limitations [122]. The Low-Income High-Cost (LIHC) indicator corrects this issue by considering also an income threshold, but, despite its relevance, the energy efficiency aspect remains not considered Then, we will place particular emphasis on three objective indicators that provide more detailed information for understanding energy poverty: Minimum Income Standard (MIS) and Low Income Low Energy Efficiency (LILEE), for disproportionate expenditure analysis considering efficiency data, and the Hidden Energy Poverty (HEP) indicator for under-consuming cases.

[10]Under this indicator, a household is considered energy poor if it has to spend more than 10% of its income in adequate energy services.

MIS: According to the definition established in [123], a household will be considered energy-poor based on the MIS if, after taking care of housing costs and other household needs, there is no budget remaining to cover the required energy costs. MIS-based indicators identify the percentage of households that would not fall below the energy poverty threshold but fall below it due to their energy expenditure. Additionally, since it is an income-based indicator, it can identify households that exhibit high vulnerability to energy poverty. This indicator significantly emphasises the economic aspect of energy poverty, highlighting that energy vulnerability stems from income inequality but also considers the influence of energy prices. However, determining the minimum income on an objective basis remains a technical challenge for MIS-based indicators.

LILEE: Under the Low-Income Low Energy Efficiency (LILEE) metric, that pursues to capture evidence from all three main drivers of energy poverty, low-income, high energy costs, and low housing efficiency, an energy poverty household has an energy efficiency rating equal or lower than D at the same time that its residual income, after deducting the costs of housing energy services, fells below the poverty line [124]. LILEE is, on the one hand, an absolute index regarding the housing energy efficiency but, on the other hand, a relative measure in terms of household income as it calculates the number of families in energy poverty and the cost necessary for them to overcome the energy poverty threshold [124]. An attractive feature of LILEE is considering an energy poverty gap that represents the difference in the necessary energy costs considering the dwelling efficiency rating and the amount of money required to defeat energy poverty.

HEP: Low-income households regularly adopt strategies to lower their energy consumption despite requiring a specific consumption to meet their essential energy needs, given their inability to pay for it. The term Hidden Energy Poverty (HEP) seeks precisely to refer to these self-imposed conditions that are too complex to identify by other metrics used to measure energy poverty and, therefore, lack regulatory approaches to mitigate it [125]. HEP metrics can be divided into two categories depending on the required energy expenditure threshold: relative-based and absolute-based energy expenditure thresholds. The thresholds of the former category are calculated based on the median or average values of similar households. The latter models the required energy expenditure of a household identifying as energy poor those that don't match the threshold [126]. In this way, it is possible to identify those users who are not consuming the energy they should consume to meet their basic needs.

Despite energy poverty being a multidimensional concern, considering the aforementioned indicators within the context of a just energy transition allows a complete integration of many household characteristics that can also be affected by long-term decision-making. Since energy prices are essential for all three indicators, the consequences of maintaining energy security despite external situations that modify energy prices can be considered to measure its effect on vulnerable households. Measuring HEP shows that despite energy availability, i.e., energy access, households are not guaranteed to consume the essential energy they need. In this way, using energy poverty analysis to evaluate transitional pathways can serve as a way to address the direct impact on vulnerable households and society through energy sector decisions and determine how energy policies can mitigate or exacerbate inequalities in many dimensions.

4.3. Integration of energy poverty analysis in Just energy transition

Addressing energy poverty in the just energy transition framework takes many challenges; some of them are technical-related to the comprehensive characterisation of the energy system, including primary energy sources, conversion of energy, energy services and energy consumers, among others, and some of them are associated to regulatory and political approaches to mitigate it. It also contributes in many areas. Firstly, an energy poverty approach for a just energy transition can help identify vulnerable people globally, not only energy-poor ones, evidencing inequalities based on income, employment, housing, energy needs supply, exposure to pollution, contribution to GHG emissions, etc. This is central to a just energy transition since identifying and dealing with inequalities, following the energy justice framework, can lower the energy required to secure universal decent living [127, 128]. Second, it helps to evaluate low-carbon transition effects on society, especially on the most vulnerable. Trade-offs between social goals to mitigate social inequalities and climate goals to improve environmental issues are needed since there is evidence that the impacts on vulnerable communities will worsen since the material basis, ecological and economic impacts to cover the new energy demand will not be equally distributed. Finally, including energy poverty analysis in a just energy transition pathway highlights policy and regulatory decisions to address energy vulnerability alleviation while enabling a low-carbon future with a more just level of resource consumption so that the needs of all people can be met while also ensuring justice between species and a stable Earth system [54, 55, 129]. However, being at the centre of the just energy transition, energy poverty partially addresses the energy justice challenges. A special focus on addressing access, security, democracy, and other climate challenges is necessary to create an environment where the just energy transition can holistically be achieved.

4.4. Operationalising the Energy Justice framework for energy poverty mitigation.

After understanding the challenges of just energy transition and the importance of energy poverty, in the case of developed countries, we come to the point where it is necessary to focus: the operationalisation of the problem. The first step to do this lies in representing residential consumers to effectively address energy poverty causes, clarify its consequences, better understand ways to cope with it, and evaluate the trade-offs of doing it is required for just decision-making. Assessment of energy poverty going from macro-to-micro perspectives include characteristics associated with its economic, social and environmental aspects [121]. Analysing energy poverty and its metrics and understanding long-term energy modelling with the requirements at the energy cycle it needs to consider, allows us to compile in Table 3, the parameters required for a broad representation of households in a just energy transition from different assessment levels and considering economic, social, technological and policy dimensions.

They are divided into eight data categories, each in its ideal required parameters for its representation. Energy service-based data (A) provides insights into the amount of energy consumed in different regions, its purpose, supplied energy services, the energy required to meet consumers' essential services and its cost. It establishes a possibility from the energy-service perspective to assess energy poverty contributing to integrating characteristics associated with energy security and access to competitive energy prices. Local energy ministries and international agencies as the IEA usually provide this data. However, regarding A4, additional techniques are necessary. Barrella et al. present an approach in this direction [126]. Representing economical-based data (B) is necessary for identifying vulnerable groups and their needs, e.g., economic alleviation. For this purpose, representing income by deciles and expenditures on energy by those income deciles will reveal inequalities related to household income expenditure. This category integrates the economic characteristics of households, allowing evidence of the consequences of the impact on their economy associated with the cost of living, including energy prices. It is important to point out that, although this proposal represents a significant step forward in the endogenous treatment of the energy justice dimension, and in particular of energy poverty, in long-term planning models, it is still very convenient to complement the study with ex-post analyses that scrutinise in detail such key elements for understanding the dynamics of energy poverty as income channels and other socio-economic variables of the household. National statistics offices collect and publish this kind of data. In particular, the EU statistics on income and living conditions (EU-SILC) provide data associated with this category for member states. Dwelling conditions (C) allow identifying households to be more likely to face high energy costs due to poor energy performance, i.e., the building's age and status. Dwelling typology data (D) helps to understand the internal conditions of a building. In this case, both data categories, (C) and (D), include housing characteristics and will shed light on the interventions needed to improve energy efficiency at the home level, proper energy access, consumption, and adjusted

Table 3
Input requirements for a wide representation of households in a just energy transition. [26, 121, 124, 124–126, 130, 131]

Data Category	Description	Parameter[a]
A: Energy-Service-based	Information related to the energy consumed and required including the costs of energy	**A1:** Energy consumed by region **A2:** Energy consumed per end-use **A3:** Energy services (Space Heating and cooling, water heating, lighting, cooking, communication technology) **A4:** Final energy required to meet essential services **A5:** Energy prices (Fuel oil, biomass, coal, district heating, household gas, household electricity)
B: Economical-based	Information about people's social and economic characteristics	**B1:**Income by deciles **B2:**Share of energy expenditure by income decile **B3:**Housing expenditure **B4:**Other expenditures[c]
C: Dwelling conditions	State or quality of a housing unit, taking into account aspects such as its structural integrity, functionality	**C1:**Efficiency label **C2:**Construction years **C3:**Conservation status
D: Dwelling typology	Physical characteristics of a housing unit, including aspects such as its size, layout, and availability of basic amenities.	**D1:**Block Dwelling/House **D2:** Urban/Rural **D3:** Walls **D4:**Pavement **D5:**Ceilling/roof **D6:**Glazing **D7:**Ventilation **D8:**Climatisation tech
E: Household-based	Demographic characteristics of a group of people who live together in a household	**E1:**Number of members **E2:**Ages **E3:**Gender **E4:**Occupancy rate **E5:**Level of ownership/tenure of the house **E6:**Employment status[d] **E7:**Health conditions **E8:** Educational level
F: Climate region	Geographic area with a similar climate pattern characterized by temperature, precipitation, humidity, and other meteorological variables.	**F1:**Outdoor temperature **F2:**Humidity **F3:**Precipitation **F4:**Solar radiation **F5:**Wind speed
G: Decentralised technology[b]	Information about an operational strategy or energy technology placed at the consumption phase	**G1:**Demand-side strategies **G2:**Distributed energy **G3:**Energy communities
H: Alleviation policies	Actions and strategies implemented to reduce energy poverty	**H1:**Energy bill assistance **H2:**Energy efficiency upgrade. **H3:** Social tariff subsidies **H4:** Social housing **H5:** Vital-minimum supply

[a] Parameters can be included endogenously and exogenously.
[b] Access to decentralised technologies will affect household energy prices as they can perform as prosumers.
[c] Includes transportation expenditures.
[d] It does not include the amount of employment generated or affected by the energy transition

energy bills to increase well-being. This assessment of energy poverty integrates social and environmental aspects into the discussion. This data can be considered by housing surveys but it might be challenging to collect. Household-based data (E) delivered by population census provides significant insights into energy needs and consumption patterns at a micro level depending on demographic household characteristics. Larger families require more energy to meet their needs, and households with elderly or young members may have different consumption requirements. Data category (F) characterises consumers based on their location's geographical conditions. People can be more or less vulnerable to energy poverty due to their location, exposure to different climate conditions, and the likelihood of using renewable energy. Then, a characterisation of consumers with access to decentralised technologies is also required (G) since they offer a potential solution for providing reliable and affordable energy to communities that may be underserved by centralised energy systems providing households with energy independence, moving towards new business models, e.g., energy communities[11]. The characteristics of energy security and reliable energy access are then included from a system and household perspective of energy poverty. Lastly, characterising the households with the presence or absence of political actions (H) will allow their evaluation, understand how they mitigate energy poverty, and identify the disparities in policy implementation and effectiveness across different regions or population groups. Government agencies often publish reports and publications that include data on the prevalence of energy poverty. This is a macro assessment of the social dimension of energy poverty. The characterisation of residential energy demand represents the first step towards operationalising the energy justice framework. Subsequently, it needs to be included in the tools that support decision-making for a just energy transition. Although modelling has been widely used for analysing energy pathways, there is little knowledge about how computer-based models actually integrate energy poverty characteristics and to what extent they contribute to just energy transitions.

5. Assessing Models Performance in Capturing Energy Poverty for a Just Energy Transition

We will analyse how close existent energy models are to represent the proposed energy justice framework for developed countries and what remains to be done. As said previously, energy modelling is a technique that allows to incorporate specific interests, define boundaries, and provide valuable insights to develop an energy transition that aligns with operationalising energy justice. However, they have often been targeted for focusing on techno-economic aspects and neglecting considerations of justice. This longstanding discussion highlights the potential benefits and harms decision-making processes can have on the environment and society [132]. This is because, traditionally, these models have not been designed with the dimension of justice in mind. To effectively incorporate justice concerns and facilitate the integration of new technologies, it is

[11] Energy communities refer to structured collaborations within energy systems, in which end-users, including individuals, businesses, and governmental bodies, fulfil their energy requirements through a collaborative strategy involving decentralized energy generation methods that emphasize the utilization of renewable energy sources.

crucial for energy modelling to be framed in a coherent and rigorous energy justice framework. The latter acknowledges that energy modelling alone is insufficient to drive change; it necessitates the support of comprehensive policies and regulations to achieve an energy transition that fosters energy justice, particularly in the context of energy poverty as well as a participative decision-making process that can profit of the use of models [133].

5.1. Are models framed for a just energy transition in developed countries?

The extent of how models support (or not) a just energy transition has been recently addressed by analysing input parameters, optimisation processes, and output discussions [19, 21, 134]. Nonetheless, despite efforts of integrating justice principles [21], approaches to modelling often lack including energy justice discourses [19]. Here, we will take a step forward to briefly show how the decision support tools used to analyse energy transition pathways, either in their original form or in extended versions, allow evaluation of energy strategies to inform stakeholders under the proposed conceptual structure of an energy poverty-centred just energy transition. We conducted an analysis in which we included 37 models that were selected based on their relevance to energy planning regarding their model type, time scale, and horizon times. Then, they were filtered to leave only those with an approach that included techno-economic, environmental and social aspects (those related to the final energy consumption). There are 26 energy models in total, none explicitly including an analysis under the energy justice framework. Table 4 provides a comparative analysis of these models, highlighting the extent to which they, exogenously or endogenously, incorporate parameters from Table 3 related to consumer household characteristics. By examining this, we can gain insights into awareness of the justice dimension of energy transition, most notably energy poverty.

5.2. Models as a tool for the just energy transition

Although many approaches already go beyond cost-optimisation objectives, relevant challenges remain. They are related to the complexity of representing rigorously residential energy demand, model limitations, or that the engagement of modellers has been along different pathways to that of energy justice, i.e., models are not built to provide or receive energy justice-related information. However, they have to be addressed to generate impact. The data category A is the best represented in models since it includes the basis for every energy planning study, e.g., energy consumed and energy prices. However, models except [161] and [156] fail to represent the required energy for meeting essential energy needs vital for energy poverty evaluation. Despite some exceptions ([156–158, 160, 162]), models fail to add household characteristics and their economic situation to study energy poverty on a general level (Categories B, C, D and E) and the approaches to deal with it (Category H). The contrasts of Category F (inclusion of F4 and F5 over F1, F2, and F3), despite some exceptions, evidence the interest of models to analyse the advantages and disadvantages of integrating wind and solar energy from a particular region rather than the energy requirements in that region, e.g., heating or cooling. The effect of energy communities (G3) has not been considered. Approaches such as the Times-Actors-Model-Households[12] (TAM-HH) [156], the National Energy Modelling System[13] (NEMS) [157], and Energy System Modelling Environment [14](ESME) [160] are the tools that include the higher number of necessary features within the Energy Justice framework. Notwithstanding, [158] has been used particularly in analysing the distributional consequences of the just energy transition [163–165]. TAM-HH was expanded in [166] in a particular way integrating household disaggregation to analyse energy poverty, access and affordability in the energy transition. Approaches based on the Decent Living Energy [159, 167, 168], provide distributional effects analysis of specific policies towards net-zero [162]. NEMS, has a broader representation of the residential sector due to integrating a residential demand module (RDM). The RDM utilises data from NEMS, including energy prices and macroeconomic indicators, to produce the necessary outputs for the integration process in NEMS. Using these inputs, the RDM generates energy consumption projections based on energy consumption components, including, e.g. personal disposable income, categorised by fuel type and census division in the residential sector. Thus, equilibrium energy prices and quantities can be calculated. PRIMES[15], within the residential sector, energy serves as an input for various processes that deliver essential services to households, including space heating, water heating, cooking, cooling, lighting, and other requirements. However, being an energy system model similar to GCAM, it faces greater difficulty to include non-energy related data. Different to more economic models as USREP and WITCH. The determination of energy consumption levels is closely linked to the demand for these services, considering factors such as efficiency, economics (such as costs and prices), and the influence of income on service demand from energy sources. Yet, energy poverty is not considered. In summary, this analysis emphasises the limitations of current models in adequately portraying the various dimensions of energy consumption in households relevant to achieving an energy transition framed by energy justice. These models fail to capture the intricate complexities of energy planning and present significant obstacles in accurately addressing the energy requirements of diverse household segments. To address these challenges, future research endeavours

[12]This model focuses on extracting the household sector out of the TIMES-Germany model and further expanding the household sector model beyond the objective of minimising costs to include maximising benefits.

[13]It is a computer-based energy-economy modelling system for the United States. Incorporates various factors, including macroeconomic and financial conditions, global energy markets, availability and costs of resources, criteria for behavioural and technological choices, characteristics of technologies, and demographic considerations.

[14]ESME is a Monte Carlo model which considers the uncertainty in this problem, particularly the uncertainty in future energy prices and the future cost and performance of energy technologies.

[15]The Price-Induced Market Equilibrium System model consists of multiple sub-models or modules, each representing the actions and characteristics of different energy supply and demand agents.

Table 4
Models

Ref	Model	A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	D1	D2	D3	D4	D5	D6	D7	D8	E1	E2	E3	E4	E5	E6	E7	E8	F1	F2	F3	F4	F5	G1	G2	G3	H1	H2	H3	H4	H5
[135]	Enertile	X	X			X																											X	X								
[136]	SNOW-NO	X	X	X																																						
[137]	GCAM	X	X	X		X	X																																X			
[138]	GEM-E3	X	X	X		X			X		X																X						X	X								
[139]	GAINS	X	X	X																																						
[140]	FORECAST	X	X	X		X															X									X												
[141]	C3IAM	X	X	X			X																										X	X								
[142]	OSeMOSYS	X	X	X		X	X																										X	X		X						
[143]	GRACE	X				X	X																										X	X		X						
[144]	REMIND	X	X	X		X								X																			X	X		X						
[145]	LEAP	X	X	X		X																	X	X						X			X	X	X	X						
[146]	PROMETHEUS	X	X	X		X	X	X			X										X												X	X					X			
[147]	EnergyPLAN	X	X	X		X					X										X									X			X	X								
[148]	WITCH	X	X	X		X	X																					X					X	X								
[149]	calliope	X	X	X		X																											X	X	X	X						
[150]	IMAGE	X	X	X		X	X														X										X	X	X	X								
[151]	DART	X	X		X	X	X	X	X					X	X																		X	X								
[152]	TAM	X	X	X		X	X				X																						X	X		X						
[153]	TIMES	X	X	X		X					X			X																X			X	X	X							
[154]	MESSAGEix-GLOBIOM	X	X	X		X	X	X						X							X	X											X	X								
[155]	PRIMES	X	X	X		X	X	X			X										X	X					X						X	X	X	X						
[156]	TAM-HH	X	X	X	X		X	X	X	X				X	X							X				X									X	X						
[157]	NEMS	X	X	X		X	X	X	X		X			X	X						X	X			X	X							X	X	X	X		X	X			
[158]	USREP	X	X				X	X		X	X																						X	X					X			
[159]	Millward et al	X	X	X								X		X																X						X						X
[160]	ESME	X	X	X		X	X	X			X	X	X	X						X	X	X			X	X							X	X	X	X			X			

should concentrate on constructing comprehensive models encompassing a broad spectrum of household energy consumption patterns, duly considering factors such as income disparities, socio-economic aspects, and behavioural dynamics.

5.3. *Regulatory and policy interventions are essential to ensure energy justice.*

Once the framework for understanding and operationalising energy justice has been set out, it becomes clear that one model does not solve everything. An energy justice-aware regulatory and policy foundation is additionally necessary to ensure the energy transition is just. Policy and regulatory assessments provide a qualitative and context-specific lens that models often lack. They offer a crucial layer of understanding, delving into the sociopolitical, cultural, and historical aspects that are challenging to quantify. Integrating regulatory assessments can guarantee that the mathematical models utilised in decision-making are based on realistic assumptions, which can inform effective policy decisions. Mathematical modelling alone cannot bring about change and requires supportive policies and regulations to achieve a just energy transition that addresses energy poverty and other social inequalities. A fair approach to energy transition planning is vital to prevent the adoption of new technologies or infrastructure changes from disproportionately impacting low-income households. Therefore, a regulatory and energy policy foundation is essential in providing a framework that promotes a just energy transition that considers social, economic, and environmental sustainability aspects. This makes it necessary to consider models including household characteristics to represent residential energy consumers broadly. This approach acknowledges the role of modelling while accentuating that it's not a panacea. It highlights the nuances of justice that may be overlooked in models and underscores the critical role of policy and regulatory assessments in achieving a just energy transition.

6. Conclusions

Confronting the adverse ecological effects of climate change simultaneously with its social justice implications is a complex task. This paper offers a comprehensive analysis among energy justice, energy transition, and energy poverty concepts establishing, from the contextualisation of justice, a non-normative framework to quantitatively integrate energy justice into long-term energy models, thereby supporting a just energy transition for developed countries.

We consider that a just energy transition is not just a transition to a low-cost, low-carbon intensive energy future. Besides, this transition should fairly and equitably confront the required adjustments of the energy system to reach a just and equitable society within environmental boundaries. We see sustainability as the underlying rationale representing this global challenge establishing the need for transformation considering that (1) the level of social welfare and well-being should not decline, (2) while respecting socio-environmental boundaries, and (3) promoting fair distribution. Although the justice element appears in this third condition, we consider that it does not capture the complexities inherent in this dimension. A comprehensive integration of justice into energy systems is proposed as an attempt to transform them into truly sustainable ones. In this sense, framed within an energy justice decision-making approach that states that energy systems should promote i) availability, ii) affordability, iii) due process, iv) transparency and accountability, v) sustainability, vi) intra and vii) inter-generational equity and viii) responsibility, we establish four consolidated quantifiable dimensions —energy access, energy democracy, energy security and energy poverty— that might serve as a proxy mechanism for measuring justice in long-term energy models and for designing future just energy systems. We consider that approaching energy justice should extend beyond distributional impact assessment, although it covers a fundamental aspect. Instead, we suggest that implementing energy justice in the full cycle of energy systems requires a holistic approach while encompassing the four quantifiable dimensions of energy justice We outline the quantifiable dimensions of energy justice to highlight the specific justice aspects they address, clarify their limitations, and identify potential trade-offs. As a result of our analysis, after proposing strategic actions to assess energy justice through the energy system process, and after establishing long-term energy modelling as a fundamental tool in designing the transition, energy poverty stands as a key factor in the context of developed countries.

Therefore, as a first step to quantify the impacts of the energy transition on vulnerable households, considering the multidimensional nature of energy poverty, a detailed representation of the energy aspects associated with the residential sector within long-term energy planning models is necessary. This paper proposes a set of 41 essential parameters divided into eight categories to be included in energy models and make energy justice operative through the lens of energy poverty. Yet, our study reveals a significant gap in a sample of existing energy planning models regarding including parameters related to consumer household characteristics, particularly those associated with energy poverty. The absence of such crucial parameters limits the accuracy and effectiveness of these models in informing decision-making processes for a just energy transition.

Besides, while quantitative modelling is an indispensable instrument in shaping informed energy policies, it has inherent limitations to comprehensively encompass the nuanced dimensions of energy justice, notably energy democracy. Taking it into account goes beyond the computational exercise itself and needs to be addressed in a more extensive way. This dimension demands stakeholder-driven participation approaches to gather insights for scenario-building and energy-modelling considerations. This could enrich the quality and viability of proposed energy scenarios, enabling debates around energy futures while building trust and fostering collaboration. Our approach aims to provide one perspective on fair outcomes in long-term energy planning, without claiming to offer an exhaustive or absolute measure of justice. In this sense, we call for continued academic efforts to refine and expand quantitative approaches, fostering a deeper understanding of justice in energy transitions that support more equitable policy frameworks.

References

[1] IPCC, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2023) 184doi:10.59327/IPCC/AR6-9789291691647.

[2] The paris agreement | UNFCCC.

[3] V. Viguié, S. Juhel, T. Ben-Ari, M. Colombert, J. D. Ford, L. G. Giraudet, D. Reckien, When adaptation increases energy demand: A systematic map of the literature, Environmental Research Letters 16 (3) (2021) 033004, publisher: IOP Publishing. doi:10.1088/1748-9326/abc044.

[4] R. Mutschler, M. Rüdisüli, P. Heer, S. Eggimann, Benchmarking cooling and heating energy demands considering climate change, population growth and cooling device uptake, Applied Energy 288 (2021) 116636. doi:10.1016/j.apenergy.2021.116636.

[5] EPAH, The leading EU initiative on local action against energy poverty. URL https://energy-poverty.ec.europa.eu/about-us_en

[6] J. Weber, H. U. Heinrichs, B. Gillessen, D. Schumann, J. Hörsch, T. Brown, D. Witthaut, Counter-intuitive behaviour of energy system models under CO2 caps and prices, Energy 170 (2019) 22–30. doi:10.1016/j.energy.2018.12.052.

[7] B. Sovacool, R. Heffron, D. McCauley, A. Goldthau, Energy decisions reframed as justice and ethical concerns, Nature Energy 1 (2016). doi:10.1038/nenergy.2016.24.

[8] R. J. Heffron, D. McCauley, The concept of energy justice across the disciplines, Energy Policy 105 (2017) 658–667. doi:10.1016/J.ENPOL.2017.03.018.

[9] B. K. Sovacool, M. H. Dworkin, Energy justice: Conceptual insights and practical applications, Applied Energy 142 (2015) 435–444. doi:10.1016/j.apenergy.2015.01.002.

[10] G. Pellegrini-Masini, A. Pirni, S. Maran, Energy justice revisited: A critical review on the philosophical and political origins of equality, Energy Research Social Science 59 (2020) 101310. doi:https://doi.org/10.1016/j.erss.2019.101310. URL https://www.sciencedirect.com/science/article/pii/S2214629618303906

[11] N. Wood, Problematising energy justice: Towards conceptual and normative alignment, Energy Research Social Science 97 (2023) 102993. doi:https://doi.org/10.1016/j.erss.2023.102993. URL https://www.sciencedirect.com/science/article/pii/S2214629623000531

[12] N. Van Uffelen, B. Taebi, U. Pesch, Revisiting the energy justice framework: Doing justice to normative uncertainties, Renewable and Sustainable Energy Reviews 189 (2024) 113974. doi:https://doi.org/10.1016/j.rser.2023.113974. URL https://www.sciencedirect.com/science/article/pii/S1364032123008328

[13] E. Laes, G. Bombaerts, A. Spahn, Towards a Pragmatic and Pluralist Framework for Energy Justice, Philosophy & Technology 36 (3) (2023) 53. doi:10.1007/s13347-023-00654-3. URL https://doi.org/10.1007/s13347-023-00654-3

[14] S. Droubi, R. J. Heffron, D. McCauley, A critical review of energy democracy: A failure to deliver justice?, Energy Research Social Science 86 (2022) 102444. doi:10.1016/j.erss.2021.102444.

[15] D. McCauley, R. Heffron, Just transition: Integrating climate, energy and environmental justice, Energy Policy 119 (2018) 1–7. doi:10.1016/j.enpol.2018.04.014.

[16] B. K. Sovacool, How long will it take? conceptualizing the temporal dynamics of energy transitions, Energy Research & Social Science 13 (2016) 202–215, energy Transitions in Europe: Emerging Challenges, Innovative Approaches, and Possible Solutions. doi:https://doi.org/10.1016/j.erss.2015.12.020.

[17] K. H. Godswill Agbaitoro, M. Wewerinke-Singh, Energy justice discourse: Global south perspectives, Journal of Energy & Natural Resources Law 42 (3) (2024) 251–254. arXiv:https://doi.org/10.1080/02646811.2024.2368985, doi:10.1080/02646811.2024.2368985. URL https://doi.org/10.1080/02646811.2024.2368985

[18] J. C. Romero, P. Linares, Multiple Criteria Decision-Making as an Operational Conceptualization of Energy Sustainability, Sustainability 13 (21) (2021) 11629, number: 21 Publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/su132111629.

[19] K. E. Lonergan, N. Suter, G. Sansavini, Energy systems modelling for just transitions, Energy Policy 183 (2023) 113791. doi:10.1016/j.enpol.2023.113791.

[20] E. Baker, S. Carley, S. Castellanos, D. Nock, J. F. Bozeman, D. Konisky, C. G. Monyei, M. Shah, B. Sovacool, Metrics for Decision-Making in Energy Justice, Annual Review of Environment and Resources 48 (1) (2023) 737–760. doi:10.1146/annurev-environ-112621-063400. URL https://www.annualreviews.org/doi/10.1146/annurev-environ-112621-063400

[21] O. Vågerö, M. Zeyringer, Can we optimise for justice? reviewing the inclusion of energy justice in energy system optimisation models, Energy Research & Social Science 95 (2023) 102913. doi:10.1016/j.erss.2022.102913.
[22] B. K. Sovacool, Energy security: challenges and needs 1 (1) 51–59. doi:10.1002/wene.13.
[23] B. W. Ang, W. L. Choong, T. S. Ng, Energy security: Definitions, dimensions and indexes 42 1077–1093. doi:10.1016/j.rser.2014.10.064.
[24] P. Sankhyayan, S. Dasgupta, 'availability' and/or 'affordability':what matters in household energy access in india?, Energy Policy (2019). doi:10.1016/J.ENPOL.2019.04.019.
[25] M. González-Eguino, Energy poverty: An overview, Renewable and Sustainable Energy Reviews 47 (2015) 377–385. doi:10.1016/J.RSER.2015.03.013.
[26] S. Sareen, H. Thomson, S. T. Herrero, J. P. Gouveia, I. Lippert, A. Lis, European energy poverty metrics: Scales, prospects and limits, Global Transitions 2 (2020). doi:10.1016/j.glt.2020.01.003.
[27] R. P. Thombs, When democracy meets energy transitions: A typology of social power and energy system scale, Energy Research Social Science 52 (2019) 159–168. doi:10.1016/j.erss.2019.02.020.
[28] C.-W. Shyu, A framework for 'right to energy' to meet UN SDG7: Policy implications to meet basic human energy needs, eradicate energy poverty, enhance energy justice, and uphold energy democracy 79 102199. doi:10.1016/j.erss.2021.102199.
[29] B. van Veelen, D. van der Horst, What is energy democracy? connecting social science energy research and political theory 46 19–28. doi:10.1016/j.erss.2018.06.010.
[30] K. Szulecki, I. Overland, Energy democracy as a process, an outcome and a goal: A conceptual review, Energy Research & Social Science 69 (2020) 101768. doi:10.1016/j.erss.2020.101768.
[31] I. J. Pérez-Arriaga, New regulatory and business model approaches to achieving universal electricity access, Papeles de energía (2017) 37–77Accepted: 2018-02-12T14:37:22Z.
[32] Y. Sokona, Y. Mulugetta, H. Gujba, Widening energy access in africa: Towards energy transition, Energy Policy 47 (2012) 3–10. doi:10.1016/J.ENPOL.2012.03.040.
[33] A. Acheampong, M. Erdiaw-Kwasie, M. Abunyewah, Does energy accessibility improve human development? evidence from energy-poor regions, Energy Economics 96 (2021) 105165. doi:10.1016/J.ENECO.2021.105165.
[34] E. F. Schumacher, G. Kirk, Schumacher on Energy: Speeches and Writings of E.F. Schumacher, Cape, 1977.
[35] I. E. Agency, Net zero by 2050: A roadmap for the global energy sector, Technical report (2021).
URL https://www.iea.org/reports/net-zero-by-2050
[36] I. E. Agency, Global energy review 2021: Assessing the effects of economic recoveries on global energy demand and CO2 emissions in 2021.
[37] THE 17 GOALS | Sustainable Development.
URL https://sdgs.un.org/goals
[38] A european green deal.
URL https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[39] K. Araújo, The emerging field of energy transitions: Progress, challenges, and opportunities, Energy Research & Social Science 1 (2014) 112–121. doi:10.1016/j.erss.2014.03.002.
[40] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. De Souza Noel Simas Barbosa, M. Fasihi, S. Khalili, T. Traber, C. Breyer, Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, Energy 227 (2021) 120467. doi:https://doi.org/10.1016/j.energy.2021.120467.
[41] K. Hainsch, K. Löffler, T. Burandt, H. Auer, P. C. del Granado, P. Pisciella, S. Zwickl-Bernhard, Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the eu green deal?, Energy 239 (2022). doi:10.1016/j.energy.2021.122067.
[42] A. Gulagi, M. Alcanzare, D. Bogdanov, E. Esparcia, J. Ocon, C. Breyer, Transition pathway towards 100 doi:10.1016/j.rser.2021.110934.
[43] S. Bolwig, T. F. Bolkesjø, A. Klitkou, P. D. Lund, C. Bergaentzlé, K. Borch, O. J. Olsen, J. G. Kirkerud, Y. kuang Chen, P. A. Gunkel, K. Skytte, Climate-friendly but socially rejected energy-transition pathways: The integration of techno-economic and socio-technical approaches in the nordic-baltic region, Energy Research & Social Science 67 (2020) 101559. doi:10.1016/j.erss.2020.101559.
[44] G. H. Brundtland, Our common future (1987).
[45] W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, S. Sörlin, Planetary boundaries: Guiding human development on a changing planet, Science 347 (6223) (2015) 1259855. doi:10.1126/science.1259855.
[46] IPCC, Working-Group-II, Climate change 2022: Impacts, adaptation and vulnerability (2022).
[47] J. D. Sachs, G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, J. Rockström, Six transformations to achieve the sustainable development goals, Nature Sustainability 2 (9) (2019) 805–814.
[48] K. O'Brien, The great transformation: shifting from fossil capital toward sustainability, Global Environmental Change 26 (2014) 1–5.
[49] F. Teulon, Economic growth and energy transition: Overview and review of the literature, The Journal of Energy and Development 40 (1/2) (2014) 247–262.
[50] K. W. Robert, T. M. Parris, A. A. Leiserowitz, What is sustainable development? goals, indicators, values, and practice, Environment: Science and Policy for Sustainable Development 47 (3) (2005) 8–21. doi:10.1080/00139157.2005.10524444.
[51] S. Sterling, Sustainable education: Re-visioning learning and change, Schumacher Briefings, Green Books, 2004.
[52] K. Raworth, Doughnut economics: Seven ways to think like a 21st-century economist, Chelsea Green Publishing, 2017.
[53] J. Rockstrom, W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, J. A. Foley, A safe operating space for humanity 461 (7263) 472–475, number: 7263 Publisher: Nature Publishing Group. doi:10.1038/461472a.
[54] J. Rockström, J. Gupta, D. Qin, S. J. Lade, J. F. Abrams, L. S. Andersen, D. I. Armstrong McKay, X. Bai, G. Bala, S. E. Bunn, D. Ciobanu, F. DeClerck, K. Ebi, L. Gifford, C. Gordon, S. Hasan, N. Kanie, T. M. Lenton, S. Loriani, D. M. Liverman, A. Mohamed, N. Nakicenovic, D. Obura, D. Ospina, K. Prodani, C. Rammelt, B. Sakschewski, J. Scholtens, B. Stewart-Koster, T. Tharammal, D. van Vuuren, P. H. Verburg, R. Winkelmann, C. Zimm, E. M. Bennett, S. Bringezu, W. Broadgate, P. A. Green, L. Huang, L. Jacobson, C. Ndehedehe, S. Pedde, J. Rocha, M. Scheffer, L. Schulte-Uebbing, W. de Vries, C. Xiao, C. Xu, X. Xu, N. Zafra-Calvo, X. Zhang, Safe and just earth system boundaries 1–10Publisher: Nature Publishing Group. doi:10.1038/s41586-023-06083-8.
[55] J. Gupta, D. Liverman, K. Prodani, P. Aldunce, X. Bai, W. Broadgate, D. Ciobanu, L. Gifford, C. Gordon, M. Hurlbert, C. Y. A. Inoue, L. Jacobson, N. Kanie, S. J. Lade, T. M. Lenton, D. Obura, C. Okereke, I. M. Otto, L. Pereira, J. Rockström, J. Scholtens, J. Rocha, B. Stewart-Koster, J. David Tàbara, C. Rammelt, P. H. Verburg, Earth system justice needed to identify and live within earth system boundaries 1–9Publisher: Nature Publishing Group. doi:10.1038/s41893-023-01064-1.
[56] J. C. Romero, Measuring energy sustainability : a new operational framework based on weak and strong indicators.
[57] A. M. Foley, B. P. Ó Gallachóir, J. Hur, R. Baldick, E. J. McKeogh, A strategic review of electricity systems models, Energy 35 (12) (2010) 4522–4530. doi:10.1016/j.energy.2010.03.057.
[58] S. C. Bhattacharyya, G. R. Timilsina, A review of energy system models, International Journal of Energy Sector Management 4 (4) (2010) 494–518, publisher: Emerald Group Publishing Limited. doi:10.1108/17506221011092742.
[59] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, W. Sparber, Classification and challenges of bottom-up energy system models - A review, Renewable and Sustainable Energy Reviews 129 (2020) 109917. doi:10.1016/j.rser.2020.109917.
[60] M. J. Fell, S. Pye, I. Hamilton, Capturing the distributional impacts of long-term low-carbon transitions, Environmental Innovation and Soci-

etal Transitions 35 (2020) 346–356. doi:https://doi.org/10.1016/j.eist.2019.01.007.
[61] A. Sen, Development as freedom, Oxford University Press, 1999.
[62] A. SEN, The Idea of Justice, Harvard University Press, 2009.
[63] M. C. Nussbaum, Frontiers of Justice: Disability, Nationality, Species Membership, Harvard University Press, 2006.
[64] N. Fraser, Social justice in the age of identity politics: Redistribution, recognition, and participation, Verso, 2003.
[65] I. M. Young, Justice and the politics of difference, Princeton University Press, 1990.
[66] M. C. Nussbaum, Creating capabilities: The human development approach, Harvard University Press, 2011.
[67] S. A. L. Smaal, J. Dessein, B. J. Wind, E. Rogge, Social justice-oriented narratives in European urban food strategies: Bringing forward redistribution, recognition and representation, Agriculture and Human Values 38 (3) (2021) 709–727. doi:10.1007/s10460-020-10179-6.
[68] H. Ramos, Mapping the Field of Environmental Justice: Redistribution, Recognition and Representation in ENGO Press Advocacy, The Canadian Journal of Sociology / Cahiers canadiens de sociologie 40 (3) (2015) 355–376, publisher: Canadian Journal of Sociology.
[69] K. Grange, N. Björling, L. Olsson, J. Fredriksson, Deconstructing the urban viewpoint: Exploring uneven regional development with Nancy Fraser's notion of justice, Urban Studies (2024) 00420980231214502Publisher: SAGE Publications Ltd. doi:10.1177/00420980231214502.
[70] J. RAWLS, A Theory of Justice: Original Edition, Harvard University Press, 1971.
[71] M. Hazrati, R. J. Heffron, Conceptualising restorative justice in the energy Transition: Changing the perspectives of fossil fuels, Energy Research & Social Science 78 (2021) 102115. doi:10.1016/j.erss.2021.102115.
[72] R. J. Heffron, Applying energy justice into the energy transition, Renewable and Sustainable Energy Reviews 156 (2022) 111936. doi:10.1016/j.rser.2021.111936.
[73] S. Bouzarovski, N. Simcock, Spatializing energy justice 107 640–648. doi:10.1016/j.enpol.2017.03.064.
[74] D. McCauley, V. Ramasar, R. J. Heffron, B. K. Sovacool, D. Mebratu, L. Mundaca, Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research, Applied Energy 233-234 (2019) 916–921. doi:10.1016/j.apenergy.2018.10.005.
[75] N. Willand, N. Torabi, R. Horne, Recognition justice in Australia: Hidden energy vulnerability through the experiences of intermediaries, Energy Research & Social Science 98 (2023) 103013. doi:10.1016/j.erss.2023.103013.
[76] S. Fuller, D. McCauley, Framing energy justice: perspectives from activism and advocacy 11 1–8. doi:10.1016/j.erss.2015.08.004.
[77] M. C. LaBelle, In pursuit of energy justice, Energy Policy 107 (2017) 615–620. doi:10.1016/j.enpol.2017.03.054.
[78] S. A. Malin, S. Ryder, M. G. Lyra, Environmental justice and natural resource extraction: intersections of power, equity and access, Environmental Sociology 5 (2) (2019) 109–116, publisher: Routledge _eprint: https://doi.org/10.1080/23251042.2019.1608420. doi:10.1080/23251042.2019.1608420.
[79] D. Del Bene, A. Scheidel, L. Temper, More dams, more violence? A global analysis on resistances and repression around conflictive dams through co-produced knowledge, Sustainability Science 13 (3) (2018) 617–633. doi:10.1007/s11625-018-0558-1.
[80] A. Buchmayr, E. Verhofstadt, L. Van Ootegem, G. Thomassen, S. Taelman, J. Dewulf, Exploring the global and local social sustainability of wind energy technologies: An application of a social impact assessment framework, Applied Energy 312 (2022) 118808. doi:https://doi.org/10.1016/j.apenergy.2022.118808.
[81] M. Z. Bell, Spatialising procedural justice: fairness and local knowledge mobilisation in nuclear waste siting, Local Environment 26 (1) (2021) 165–180, publisher: Routledge _eprint: https://doi.org/10.1080/13549839.2020.1867841. doi:10.1080/13549839.2020.1867841.
[82] C. Walker, J. Baxter, Procedural justice in Canadian wind energy development: A comparison of community-based and technocratic siting processes, Energy Research & Social Science 29 (2017) 160–169. doi:10.1016/j.erss.2017.05.016.
[83] I. Bailey, H. Darkal, (not) talking about justice: justice self-recognition and the integration of energy and environmental-social justice into renewable energy siting, Local Environment 23 (2018) 335 – 351. doi:10.1080/13549839.2017.1418848.
[84] K. NEUHOFF, S. BACH, J. DIEKMANN, M. BEZNOSKA, T. EL-LABOUDY, Distributional effects of energy transition: Impacts of renewable electricity support in germany, Economics of Energy & Environmental Policy 2 (1) (2013) 41–54.
[85] S. Carley, D. M. Konisky, The justice and equity implications of the clean energy transition, Nature Energy 5 (2020) 569–577. doi:10.1038/s41560-020-0641-6.
[86] N. Healy, J. Barry, Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition", Energy Policy 108 (2017) 451–459. doi:10.1016/J.ENPOL.2017.06.014.
[87] S. Bouzarovski, S. T. Herrero, The energy divide: Integrating energy transitions, regional inequalities and poverty trends in the european union, European Urban and Regional Studies 24 (1) (2017) 69–86. doi:10.1177/0969776415596449.
[88] Tracking SDG 7: The energy progress report (2021).
URL https://www.irena.org/publications/2021/Jun/Tracking-SDG-7-2021
[89] A. Wierling, V. Schwanitz, J. P. Zeiss, C. Bout, C. Candelise, W. Gilcrease, J. Gregg, Statistical evidence on the role of energy cooperatives for the energy transition in european countries, Sustainability (2018). doi:10.3390/SU10093339.
[90] M. Bueno-López, P. Rodríguez-Sánchez, M. Molinas, Sustainable model for rural electrification projects in non-interconnected areas in colombia, in: 2019 IEEE Global Humanitarian Technology Conference (GHTC), 2019, pp. 1–6. doi:10.1109/GHTC46095.2019.9033104.
[91] S. Ehsanullah, Q. Tran, M. Sadiq, S. Bashir, M. Mohsin, R. Iram, How energy insecurity leads to energy poverty? do environmental consideration and climate change concerns matters, Environmental Science and Pollution Research 28 (2021) 55041 – 55052. doi:10.1007/s11356-021-14415-2.
[92] A. B. Setyowati, Mitigating inequality with emissions? exploring energy justice and financing transitions to low carbon energy in indonesia, Energy research and social science 71 (2021) 101817. doi:10.1016/j.erss.2020.101817.
[93] B. Sovacool, M. J. Burke, L. Baker, C. K. Kotikalapudi, H. Wlokas, New frontiers and conceptual frameworks for energy justice, Energy Policy 105 (2017) 677–691. doi:10.1016/J.ENPOL.2017.03.005.
[94] V. Menghwani, H. Zerriffi, A. Korkovelos, B. Khavari, A. Sahlberg, M. Howells, D. Mentis, Planning with justice: Using spatial modelling to incorporate justice in electricity pricing – the case of tanzania, Applied Energy 264 (2020) 114749. doi:10.1016/j.apenergy.2020.114749.
[95] A. O. Acheampong, J. Dzator, M. Shahbaz, Empowering the powerless: Does access to energy improve income inequality?, Energy Economics (2021). doi:10.1016/J.ENECO.2021.105288.
[96] W. Li, F. Chien, C.-C. Hsu, Y. Zhang, M. Nawaz, S. Iqbal, M. Mohsin, Nexus between energy poverty and energy efficiency: Estimating the long-run dynamics, Resources Policy 72 (2021) 102063. doi:10.1016/J.RESOURPOL.2021.102063.
[97] J. Lewis, D. Hernández, A. Geronimus, Energy efficiency as energy justice: addressing racial inequities through investments in people and places, Energy Efficiency 13 (2019) 419–432. doi:10.1007/s12053-019-09820-z.
[98] A. Horta, J. Gouveia, L. Schmidt, J. C. Sousa, P. Palma, S. Simoes, Energy poverty in portugal: Combining vulnerability mapping with household interviews, Energy and Buildings (2019). doi:10.1016/j.enbuild.2019.109423.
[99] K. Primc, R. Slabe-Erker, Social policy or energy policy? time to reconsider energy poverty policies, Energy for Sustainable Development 55 (2020) 32–36. doi:10.1016/j.esd.2020.01.001.
[100] N. van Uffelen, Revisiting recognition in energy justice, Energy Research & Social Science 92 (2022) 102764. doi:10.1016/j.erss.2022.102764.
[101] K. Jenkins, D. McCauley, R. Heffron, H. Stephan, R. Rehner, Energy justice: A conceptual review, Energy Research Social Science 11 (2016) 174–182. doi:10.1016/j.erss.2015.10.004.

[102] S. Williams, A. Doyon, Justice in energy transitions, Environmental Innovation and Societal Transitions 31 (2019) 144–153. doi:10.1016/j.eist.2018.12.001.

[103] S. Oum, Energy poverty in the lao pdr and its impacts on education and health, Energy Policy (2019). doi:10.1016/J.ENPOL.2019.05.030.

[104] B. K. Sovacool, Deploying Off-Grid Technology to Eradicate Energy Poverty, Science 338 (6103) (2012) 47–48, publisher: American Association for the Advancement of Science. doi:10.1126/science.1222307.

[105] Research commentary: The EU commission's proposal for improving the electricity market design: Treading water, but not drowning.

[106] A. X. Hearn, A. Sohre, P. Burger, Innovative but unjust? analysing the opportunities and justice issues within positive energy districts in europe, Energy Research & Social Science 78 (2021) 102127. doi:10.1016/j.erss.2021.102127.

[107] J. P. Gouveia, J. Seixas, P. Palma, H. Duarte, H. Luz, G. B. Cavadini, Positive Energy District: A Model for Historic Districts to Address Energy Poverty, Frontiers in Sustainable Cities 3 (2021).

[108] I. Kyprianou, D. K. Serghides, A. Varo, J. P. Gouveia, D. Kopeva, L. Murauskaite, Energy poverty policies and measures in 5 EU countries: A comparative study, Energy and Buildings 196 (2019) 46–60. doi:10.1016/j.enbuild.2019.05.003.

[109] D. C. Invernizzi, G. Locatelli, A. Velenturf, P. E. Love, P. Purnell, N. J. Brookes, Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning 144 111677. doi:https://doi.org/10.1016/j.enpol.2020.111677.

[110] A. M. Feldpausch-Parker, D. Endres, T. R. Peterson, Editorial: A Research Agenda for Energy Democracy, Frontiers in Communication 4 (2019).

[111] B. K. Sovacool, An international assessment of energy security performance, Ecological Economics 88 (2013) 148–158. doi:10.1016/j.ecolecon.2013.01.019.

[112] B. K. Sovacool, H. Saunders, Competing policy packages and the complexity of energy security, Energy 67 (2014) 641–651. doi:10.1016/j.energy.2014.01.039.

[113] Ministry for Ecological Transition and Demographic Challenge, PNIEC (2023). borrador actualizado del plan nacional integrado de energía y clima 2021-2030. (2023).

[114] H.-K. Ringkjøb, P. M. Haugan, I. M. Solbrekke, A review of modelling tools for energy and electricity systems with large shares of variable renewables, Renewable and Sustainable Energy Reviews 96 (2018) 440–459. doi:10.1016/j.rser.2018.08.002.

[115] N. Neshat, M. R. Amin-Naseri, F. Danesh, Energy models: Methods and characteristics, Journal of Energy in Southern Africa 25 (4) (2014) 101–111, publisher: University of Cape Town.

[116] T. Schinko, G. Bachner, S. P. Schleicher, K. W. Steininger, Modeling for insights not numbers: The long-term low-carbon transformation, Atmósfera 30 (2) (2017) 137–161, publisher: Elsevier. doi:10.20937/ATM.2017.30.02.05.

[117] M. González-Eguino, Energy poverty: An overview, Renewable and Sustainable Energy Reviews 47 (2015) 377–385. doi:10.1016/J.RSER.2015.03.013.

[118] M. Llorca, A. Rodriguez-Alvarez, T. Jamasb, Objective vs. subjective fuel poverty and self-assessed health 87 104736. doi:10.1016/j.eneco.2020.104736.

[119] J. C. Romero, P. Linares, X. López, The policy implications of energy poverty indicators, Energy Policy 115 (2018) 98–108. doi:10.1016/j.enpol.2017.12.054.

[120] S. Pachauri, D. Spreng, Measuring and monitoring energy poverty 39 (12) 7497–7504. doi:10.1016/j.enpol.2011.07.008.

[121] I. Siksnelyte-Butkiene, D. Streimikiene, V. Lekavicius, T. Balezentis, Energy poverty indicators: A systematic literature review and comprehensive analysis of integrity 67 102756. doi:10.1016/j.scs.2021.102756.

[122] R. Schuessler, Energy Poverty Indicators: Conceptual Issues - Part I: The Ten-Percent-Rule and Double Median/Mean Indicators (May 2014). doi:10.2139/ssrn.2459404.

[123] R. Moore, Definitions of fuel poverty: Implications for policy, Energy Policy 49 (2012) 19–26, special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy. doi:https://doi.org/10.1016/j.enpol.2012.01.057.

[124] F. Belaïd, Implications of poorly designed climate policy on energy poverty: Global reflections on the current surge in energy prices 92 102790. doi:10.1016/j.erss.2022.102790.

[125] S. Meyer, H. Laurence, D. Bart, L. Middlemiss, K. Maréchal, Capturing the multifaceted nature of energy poverty: Lessons from belgium 40 273–283. doi:10.1016/j.erss.2018.01.017.

[126] R. Barrella, J. C. Romero, J. I. Linares, E. Arenas, M. Asín, E. Centeno, The dark side of energy poverty: Who is underconsuming in spain and why? 86 102428. doi:10.1016/j.erss.2021.102428.

[127] J. Millward-Hopkins, Inequality can double the energy required to secure universal decent livingdoi:10.1038/s41467-022-32729-8.

[128] Y. Oswald, J. K. Steinberger, D. Ivanova, J. Millward-Hopkins, Global redistribution of income and household energy footprints: a computational thought experiment, Global Sustainability 4 (2021) e4, publisher: Cambridge University Press. doi:10.1017/sus.2021.1.

[129] I. Lippert, S. Sareen, Alleviation of energy poverty through transitions to low-carbon energy infrastructure, Energy Research & Social Science 100 (2023) 103087. doi:10.1016/j.erss.2023.103087.

[130] R. Barrella, J. C. Romero, J. I. Linares, E. Arenas, M. Asín, E. Centeno, The dark side of energy poverty: Who is underconsuming in spain and why?, Energy Research Social Science 86 (2022) 102428. doi:10.1016/j.erss.2021.102428.

[131] K. Mahoney, J. P. Gouveia, P. Palma, (dis)united kingdom? potential for a common approach to energy poverty assessment 70 101671. doi:10.1016/j.erss.2020.101671.

[132] W. A. Wallace, Ethics in modeling (1994).

[133] D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, Model-based policymaking or policy-based modelling? How energy models and energy policy interact, Energy Research & Social Science 75 (2021) 101984. doi:10.1016/j.erss.2021.101984.

[134] A. Krumm, D. Süsser, P. Blechinger, Modelling social aspects of the energy transition: What is the current representation of social factors in energy models?, Energy 239 (2022) 121706. doi:10.1016/j.energy.2021.121706.

[135] G. Resch, J. Geipel, A. Hiesl, L. Liebmann, T. U. Wien, S. Lumbreras, L. Olmos, A. Ramos, Q. Ploussard, Navigating the roadmap for clean, secure and efficient energy innovation.
URL www.set-nav.eu

[136] CREE, SNoW-NO Statistics Norway's World Model for Norway, 2020.

[137] GCAM: Global Change Analysis Model | Global Change Intersectoral Modeling System.
URL https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

[138] P. Capros, D. van Regemorter, L. Paroussos, P. Karkatsoulis, GEM-E3 model documentation, Joint Research Centre, Institute for Prospective Technological Studies, 2020.

[139] The GAINS Model - GAINS Model - IIASA.
URL https://previous.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html

[140] T. Fleiter, M. Rehfeldt, A. Herbst, R. Elsland, A.-L. Klingler, P. Manz, S. Eidelloth, A methodology for bottom-up modelling of energy transitions in the industry sector: The forecast model, Energy Strategy Reviews 22 (2018) 237–254. doi:https://doi.org/10.1016/j.esr.2018.09.005.

[141] Y.-M. Wei, R. Han, Q.-M. Liang, B.-Y. Yu, Y.-F. Yao, M.-M. Xue, K. Zhang, L.-J. Liu, J. Peng, P. Yang, Z.-F. Mi, Y.-F. Du, C. Wang, J.-J. Chang, Q.-R. Yang, Z. Yang, X. Shi, W. Xie, C. Liu, Z. Ma, J. Tan, W. Wang, B.-J. Tang, Y.-F. Cao, M. Wang, J.-W. Wang, J.-N. Kang, K. Wang, H. Liao, An integrated assessment of INDCs under Shared Socioeconomic Pathways: an implementation of C3IAM, Natural Hazards 92 (2) (2018) 585–618. doi:10.1007/s11069-018-3297-9.

[142] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian, A. Roehrl, Osemosys: The open source energy modeling system: An introduction to its ethos, structure and development, Energy Policy 39 (10) (2011) 5850–5870, sustainability of biofuels. doi:https://doi.org/10.1016/j.enpol.2011.06.033.

[143] A. Aaheim, H. Amundsen, T. Dokken, T. Wei, Impacts and adaptation to climate change in European economies, Global Environmental Change 22 (4) (2012) 959–968. doi:10.1016/j.gloenvcha.2012.06.005.

[144] N. Bauer, L. Baumstark, M. Leimbach, The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds, Climatic Change 114 (1) (2012) 145–168. doi:10.1007/s10584-011-0129-2.

[145] C. Heaps, EnergyPLAN, Leap (long-range energy alternatives planning).
URL https://www.energyplan.eu/othertools/national/leap/

[146] PROMETHEUS – E3 Modelling.
URL https://e3modelling.com/modelling-tools/prometheus/

[147] H. Lund, J. Z. Thellufsen, EnergyPLAN - Advanced Energy Systems Analysis Computer Model (May 2022). doi:10.5281/zenodo.6602938.

[148] Model – The WITCH model.
URL https://www.witchmodel.org/model/

[149] G. Pontes Luz, R. Amaro e Silva, Modeling energy communities with collective photovoltaic self-consumption: Synergies between a small city and a winery in portugal, Energies 14 (2) (2021). doi:10.3390/en14020323.

[150] Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications | PBL Netherlands Environmental Assessment Agency.
URL https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0

[151] M. Weitzel, J. Ghosh, S. Peterson, B. K. Pradhan, Effects of international climate policy for India: evidence from a national and global CGE model, Environment and Development Economics 20 (4) (2015) 516–538, publisher: Cambridge University Press. doi:10.1017/S1355770X14000424.

[152] A. Tash, M. Ahanchian, U. Fahl, Improved representation of investment decisions in the german energy supply sector: An optimization approach using the times model, Energy Strategy Reviews 26 (2019) 100421. doi:https://doi.org/10.1016/j.esr.2019.100421.

[153] R. Loulou, E. Wright, G. Giannakidis, K. Noble, Energy technology systems analysis programme (2016).
URL http://www.iea-etsap.org/web/Documentation.asp

[154] V. Krey, P. Havlik, P. Kishimoto, O. Fricko, J. Zilliacus, M. Gidden, M. Strubegger, G. Kartasasmita, T. Ermolieva, N. Forsell, F. Guo, M. Gusti, D. Huppmann, N. Johnson, J. Kikstra, G. Kindermann, P. Kolp, F. Lovat, D. McCollum, J. Min, S. Pachauri, S. Parkinson, S. Rao, J. Rogelj, G. Unlu, H. Valin, P. Wagner, B. Zakeri, M. Obersteiner, K. Riahi, MESSAGEix-GLOBIOM Documentation - 2020 release, place: Laxenburg, Austria Publisher: IIASA (Mar. 2020). doi:10.22022/IACC/03-2021.17115.
URL https://iiasa.dev.local/

[155] PRIMES – e3 modelling.
URL https://e3modelling.com/modelling-tools/primes/

[156] P. Capros, D. van Regemorter, L. Paroussos, P. Karkatsoulis, SNoW-NO Statistics Norway's World Model for Norwa, Joint Research Centre, Institute for Prospective Technological Studies, 2020.

[157] NEMS.
URL https://www.energyplan.eu/othertools/national/nems/

[158] M. Yuan, S. Rausch, J. Caron, S. Paltsev, J. Reilly, The MIT U.S. Regional Energy Policy (USREP) Model: The Base Model and Revisions.

[159] J. Millward-Hopkins, J. K. Steinberger, N. D. Rao, Y. Oswald, Providing decent living with minimum energy: A global scenario, Global Environmental Change 65 (2020) 102168. doi:10.1016/j.gloenvcha.2020.102168.

[160] M. J. Fell, S. Pye, I. Hamilton, Capturing the distributional impacts of long-term low-carbon transitions, Environmental Innovation and Societal Transitions 35 (2020) 346–356. doi:10.1016/j.eist.2019.01.007.

[161] M. Weitzel, J. Ghosh, S. Peterson, B. K. Pradhan, Effects of international climate policy for india: evidence from a national and global cge model, Environment and Development Economics 20 (4) (2015) 516–538. doi:10.1017/S1355770X14000424.

[162] J. Millward-Hopkins, E. Johnson, Distributing less, redistributing more: Safe and just low-energy futures in the United Kingdom, Energy Research & Social Science 95 (2023) 102915. doi:10.1016/j.erss.2022.102915.

[163] S. Rausch, G. E. Metcalf, J. M. Reilly, Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households, Energy Economics 33 (2011) S20–S33. doi:10.1016/j.eneco.2011.07.023.

[164] M. Tomás, X. García-Muros, E. Alonso-Epelde, I. Arto, A. Rodríguez-Zúñiga, C. Monge, M. González-Eguino, Ensuring a just energy transition: A distributional analysis of diesel tax reform in Spain with stakeholder engagement, Energy Policy 177 (2023) 113558. doi:10.1016/j.enpol.2023.113558.

[165] X. García-Muros, J. Morris, S. Paltsev, Toward a just energy transition: A distributional analysis of low-carbon policies in the USA, Energy Economics 105 (2022) 105769. doi:10.1016/j.eneco.2021.105769.

[166] A. D. Forschungsbericht, System analysis of the significance of energy poverty on household energy use and emissions in germany.

[167] A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp, H. Valin, A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies, Nature Energy 3 (6) (2018) 515–527, number: 6 Publisher: Nature Publishing Group. doi:10.1038/s41560-018-0172-6.

[168] J. S. Kikstra, A. Mastrucci, J. Min, K. Riahi, N. D. Rao, Decent living gaps and energy needs around the world, Environmental Research Letters 16 (9) (2021) 095006, publisher: IOP Publishing. doi:10.1088/1748-9326/ac1c27.