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Review

Alleviation of energy poverty through transitions to low-carbon energy infrastructure

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ABSTRACT

With Green Deals and a competitive techno-economic basis for low-carbon energy transitions, energy infrastructural change is intensifying. This is matched by rapid growth in scholarship on sociotechnical transitions and energy justice, combined in the phrase 'just transitions'. Yet how can an abstract concern with a normative concept like justice be brought to bear on the socio-technical complexities of specific changes in energy infrastructure? This is an important and timely question to consider in a practical sense, since the energy policy landscape is increasingly focused on a 'just transition' as combining decarbonisation and a progressive vision of social equity and justice. Our synthesis review argues that a focus on the alleviation of energy poverty – a condition whereby people are unable to secure adequate levels of energy services in the home – can enable policy-oriented mobilisation of energy justice as an integral component of evolving energy infrastructure. We approach energy poverty as an opportunity to constructively broach issues of justice in global energy policy discourse, not as a catch-all for wider injustices and vulnerabilities. We present a conceptual framework, applied to three schematic cases of energy infrastructure under transition. In and across these cross-sectoral cases, we reflect on scope for energy poverty alleviation.

1. Introduction

Energy infrastructural change is intensifying thanks to a competitive techno-economic basis for low-carbon energy transitions and emerging Green Deals. Increasing scholarship on sociotechnical transitions and energy justice, combined in the phrase 'just transitions' [1,2], reflects this. So does the energy policy landscape, which increasingly connects decarbonisation with progressive visions of social equity and justice. We broach the important and timely question of how concern with justice can be brought to bear on complex socio-technical changes in energy infrastructure. We argue that a policy focus on energy poverty alleviation – a condition whereby people are unable to secure adequate levels of energy services in the home [3] – can mobilise energy justice as integral to energy infrastructural evolution (in this journal, see [4]). We approach energy poverty not as a catch-all for wider injustices and vulnerabilities, but rather as a means to interpellate global energy policy discourse with justice issues. The article presents a conceptual framework and applies it to three schematic cases of transitioning energy infrastructure. These cross-sectoral cases enable reflections on the scope to alleviate energy poverty.

Energy infrastructures – the material artefacts and social interactions that comprise any energy system – are inherently socio-material [5]. Their technical components are intricately tied together with social practices, e.g. how one cooks, commutes and does laundry, as well as how technicians read screens in control rooms. These are embedded in and co-shape each other, which has given rise to an explicit focus on socio-technical transitions among energy infrastructure scholars (although in science and technology studies, or STS, the preferred term remains socio-materiality due to an emphasis on the emergent nature of agency and the performative effects of practices [6]). Energy historians have shown how energy has been created as a particular sort of object or socio-technical imaginary [7,8] due to path dependencies and power relations during past centuries, and how this conditions current possibilities [9]. Much of this legacy is embodied in energy infrastructure itself, which layers atop itself as an encrusted manifestation of both technological evolution and societal conditioning as well as the non-

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human agency of infrastructure [10]. For instance, with car-centric infrastructure (e.g. highway networks) in place during the 20th century, the suburban form of spatial organisation has taken root in ways that have been determinative for many linked forms of energy use (automobility versus public transport, residential heating energy sources, local and global material supply chains). Understanding these driving forces is essential to identify both the limits as also the possibilities for change and pathways to mobilise new socio-technical imaginaries of energy futures [11]. In other words, low-carbon energy transitions go beyond the availability of cost-competitive renewable energy technologies, to their embedment into complex socio-technical practices [12].

Scholars of energy transitions have identified a range of justice concerns concomitant with efforts to decarbonise energy infrastructure. Incumbency politics presents a major challenge, whereby entrenched actors exercise undue influence to promote their self-interest and concentrate benefits among a few elite actors, at the expense of slowing down transitions while burdening ordinary energy users [13]. Efforts are underway to empower these users as ‘energy citizens’, for wider societal recognition of clean energy as a basic service and one that can be produced and controlled in more distributed ways [14]. This push manifests in diverse ways – as social movements for ecological change (e.g. divestment [15]), grassroots organising (e.g. energy communities [16]) and calls for changes in historical ownership structures of energy companies (e.g. remunicipalisation [17]). The nature of value creation and extraction is changing alongside energy infrastructure, with increasing rewards to ‘energy flexibility’ as more renewable energy sources are integrated into electric grids and the nature of grid management logics evolves [18]. Further, decarbonising energy systems involves electrifying multiple sectors like mobility, and increasing the energy efficiency of the built environment to limit future energy demand. Moreover, decarbonising energy systems extends beyond decarbonising the electric grid and increasing efficiency. It requires taking a wider view of linked wellbeing aspects like health, where energy retrofit investments may for instance divert funding from the replacement of coal and diesel home heating systems that adversely impact respiratory tracts. Similarly, high home insulation unaccompanied by proper ventilation standards may lower indoor air quality and increase carcinogenic radon accumulation. Decarbonisation in a holistic sense also requires addressing highly consumerist energy demand, including tackling rebound effects where affordable access to clean energy may drive higher demand with dispersed indirect costs [19]. Just transitions thus pose the challenge of real-time cross-sectoral coordination, to ensure that long-term infrastructural commitments enable low-carbon shifts in a socially inclusive and fair manner, rather than tying in infrastructure that prolongs fossil fuel use, sustains production patterns geared to incentivise high energy consumption, or concentrates benefits in some pockets while displacing the burdens to others. These are the complex and intertwined policy challenges of enabling just sustainable energy transitions [20].

The demand for a just transition (e.g. [1]), while closely related to changing energy infrastructure, has a long-running broader history. It stems from a struggle for environmental justice that is rooted in the recognition of systematic intersectional justice that cuts across lines of race, ethnicity, gender, class, caste and age. Environmental justice scholarship has a strong tradition (e.g. [21–23]) that energy scholars have adapted to the more specific concern of infrastructures such as resource extraction, transmission, last-mile distribution and use within intimate spaces like the household. This energy justice literature has unearthed socio-spatial differentiation (e.g. [2,24]), a spectrum of actors holding in place systematically inegalitarian allocations of benefits and burdens (e.g. [25,26]), and has bridged usefully with work on justice in philosophy and ethics by e.g. [27–29]. An influential policy translation function from this research into practice has taken the form of energy poverty alleviation, which has gathered a large community of research and practice with an increasingly coordinated policy agenda in Europe (e.g. [30]) backed by robust research (e.g. [3]) and global resonance [31,32]. Its influence is notable in the Sustainable Development Goal (SDG) 7 on affordable clean energy access for all and in the explicit mention of energy poverty alleviation in most National Energy and Climate Plans 2030 of European Union member states in 2019, as well as an emerging push for energy as a basic right. Yet there remains work to be done to move from these visions and statements of intent to questions of monitoring, assessment and targeted alleviation of the real-world phenomenon. This raises questions of knowability, both practical and in line with a philosophical perspective on situated knowledges [33] and the violence entailed in representation.

In Sareen et al. [34], the authors offer a framework on ‘energy poverty (EP) metrology’, i.e., the logics of metrics for energy poverty. Their framework is informed by a critical engagement with insights from the field of Science and Technology Studies (STS) in the politics of data [see also [35,36]], recognising that data themselves are an effect of social, historical as well as environmental conditions: Energy poverty can be differently measured depending on, for instance, the in- and exclusion of data sources by agents with situated interests, while temperature indicators depend on weather context, and are stirred up by climate change.

As Fig. 1 shows, Sareen et al.'s [34] framework comprises five dimensions. Starting with the historical trajectories of EP metrics, the framework considers the contingencies of how metrics of energy and fuel poverties have historically been shaped in the United Kingdom and subsequently often uncritically translated into indicators internationally [see also [35,36]]. The framework recognises that the measurement of EP is enacted and identifies a key tension in current state of-the-art of measuring EP – between data flattening (treating data from different contexts, produced in incompatible ways, as commensurable; this we read as an artefact of maximising coverage) and contextualised identification (that seeks to triangulate data from various databases and sources to generate high resolution identifiers of (hidden) EP on low scales, like household or urban district level; this we read as an artefact of maximising accuracy). Sareen et al.'s [34] framework culminates in providing a sensitivity to how EP metrics are or can be reconfigured via new forms of representation (considering for instance the data brought forward by grassroot movements; which we read as addressing emerging innovative EP metrics) and policy uptake (a process within which data choices can (re)make different versions of the energy poor and rich; which we read as the politics of EP metrics being mainstreamed).

Our conceptual framework in this paper develops this metrology in relation to low-carbon transitions and social justice. While Sareen et al.'s [34] framework is strong in attuning analysis to the politics of data, we miss a constructive take on how their critical insight can be mobilised for addressing social injustices of EP. Specifically, within enacting and reconfiguring EP measurements, we posit intersections with social justice concerns. To address such intersections, we develop a conceptual framework that extends the one proposed by Sareen et al. [34] with sensitising analytical questions that can support scholars and policy agents as well as agents of monitoring (for instance Green Deals) in analysing changes in energy infrastructure and their import for measuring EP. We recognise that our development is shaped by a widely Euro-centric position in scholarship on EP, but we seek to mitigate against provincialising the global south by indicating critical global relations and a wide range of experiences of EP. In developing this social justice attuned conceptual framework on the metrology of energy poverty, we aim at critical attention to these constructive concerns: To what extent can infrastructural change go hand in hand with innovation in and the mainstreaming of EP metrics that ensure just effects of low-carbon transition for the energy poor? How can this be done in a manner that maximises coverage and accuracy for EP metrics, despite trade-offs between the two? What are the historical legacies that we must harness and guard against to shape EP metrics as they coevolve with low-carbon energy infrastructures? We seek generative ways forward towards addressing these overarching concerns, without explicitly targeting them within the scope of this consolidatory and agenda setting

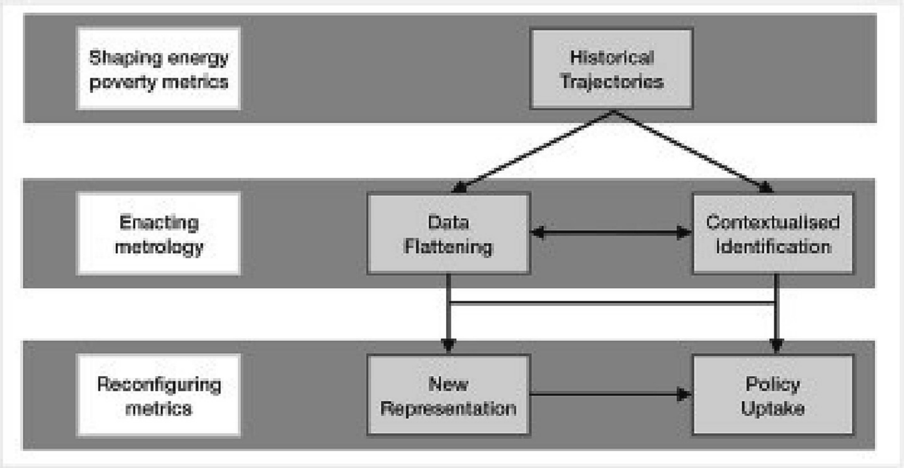

Fig. 1. Dimensions of energy poverty metrology. Source: [34]: 28, https://doi.org/10.1016/j.glt.2020.01.003.

review.

Accordingly, we proceed as follows. Section 2 presents the approach and underpinnings to develop a conceptual framework to assess sustainable energy transitions, featuring reflections drawn from the state-of-the-art on the political economy of energy infrastructure and the link between infrastructure and energy metrics. Section 3 operationalises this analytical framework by approaching energy poverty as a policy oriented mobilisation of energy justice. Section 4 applies the framework to schematic energy infrastructure transitions in three sectors: the digitisation of retail electricity, the diffusion of electric vehicles in the mobility sector, and energy efficiency measures in the built environment. Section 5 synthesises and discusses insights and concerns from across these cases. Section 6 offers our concluding reflections on current measurement gaps and scope to improve EP metrics, and on the integration of insights into national and sub-national energy policies, in line with emerging Green Deals worldwide.

2. Material and methods: towards an analytical framework to assess just sustainable energy transition

To assess energy transitions and transformations towards sustainable carbon neutrality, in this section we consider concepts of energy infrastructure and its governance via metrics, and how these are socio-technically shaped. Correspondingly, our material is thematic scholarship reviewed here, and our method is to undertake its synthesis to extract novel insights, towards making available major justice themes (Section 3), applied on questions of measuring EP (Section 4). Our reading of this scholarship builds on three decades of cumulative research experience on energy, infrastructures, metrology and environmental transitions. Together, the literatures on infrastructures, metrics and justice of energy constitute a helpful conceptual foundation to measure socio-political dimensions of energy transition.

The sub-sections on the political economy of energy infrastructure transitions and the relationship between infrastructure and metrics lay the foundation for our subsequent treatment and discussion of three schematic cases across energy related sectors (electricity, mobility and housing) in Sections 4–5 respectively. These sub-sections highlight the considerable scholarship that has come about in recent years on how transitions are politically modulated, conditioned by interests of incumbents, and how these tendencies are deeply rooted in everyday practices, notably including what metrics are used to monitor energy use and set transition targets, at what scales by which actors.

2.1. *Political economic underpinning of energy infrastructural change*

Sensitised by political economic approaches that consider the historical and material, including infrastructural, legacies of economic relations and the allocation of resources, we problematise and illustrate energy infrastructural change. With work like the Grundrisse by Karl Marx and David Harvey's body of work on space, we are sensitised to questions of control over resources. However, towards developing concepts that support contextual identification, we avoid broad generalisation and for that, we principally engage with forms of analyses in geography, sociology, anthropology and STS that attend to infrastructural components and relations on the ground (e.g. [37,38]). With these we find that the political and economic dimensions of energy are well established, including, inter alia, processes by incumbents to maintain their power of fossil fuel and nuclear energy as well as in shifts to low carbon infrastructures [1,37–39]. In the 21st century, different energy infrastructural “solution” projects are competing, foremost nuclear versus green energy [40,41]. Significant choices and pathway decisions are undertaken by civil, corporate and regulatory actors.

Energy infrastructures are owned and ownable by a very diverse set of actors. These include for-profit and not-for-profit organisations, the former typically operating as firms. The owners can be differentiated by the type of owner, such as shareholder corporations and limited companies, publicly owned organisations (for instance owned by a state) or cooperatively owned by individual customers or workers of the organisation. The energy infrastructure owners operate across different kinds of scales – locally (down to an industrial site or a household, often at the urban scale), regionally, nationally and transnationally. The owners are also marked by their historic relationship to the land on which they operate – it is thus possible to differentiate e.g. majority ethnic group owners from indigenous and autochthonous owners.

To illustrate the sensitivity of this conceptual analysis, consider this contrast between infrastructures: E.On is a supranational shareholder corporation (SE) that runs energy networks in several Western, Northern, Central and Eastern European countries, and is involved with approximately 22 million customers in eight European countries [42]. E.On runs electricity and gas networks. For 2019, it reports transmitting 192 TWh of electric power, and 135 TWh of gas [42], with the E.On operations resulting in (in)direct carbon emissions of 67.31 million metric tonnes [43]. In contrast to this supranational organisation, Denmark shows a history of individual ownership of wind turbines with “[a]lmost 80% of the total 6300 wind turbines […] in collective ownership or operated by single owners” in the late 1980s/early 1990s ([44]: 110). Vindenergi Danmark is a key case for a not-for-profit company that is community owned and purchases (at reliably fixed prices) and trades electricity for cooperative and private individual producers [44,45].

With such a heterogeneous ownership structure, profits and risks of energy infrastructure and the ability of individuals and corporations to access such infrastructure and the energy services that it enables are also very unequally distributed. This possibility of regressive allocation raises political and economic interests in energy policy, in shaping the governance of energy infrastructures. We consider two ways of expressing these interests, by way of direct contact with decision-makers (lobbyism) and by way of shaping the discourse of energy.

Energy policy frames the problems and issues it tackles in specific ways [46]. This framing ranges from assumptions about how energy is available to users, to what needs energy generation serves. For instance, energy provision can be understood as electricity and fuel, or alternatively in terms of services such as warmth, lighting and mobility. Energy policy itself is discursively constructed. This matters because different constructs silence or boost specific interests and voices. Language weaves diverse imperatives like "sustained economic growth" or "national security" into energy policy. Such impetus then feeds into energy and environmental discourses characterised by uncertainties. Divergent values and interests prevent easy resolution of uncertainties, leading to either contestation or conflict avoidance by actors who shape policy processes in the terms of the values and imperatives that best serve their own interests. A well-studied example of such discursive dynamics is nuclear energy [41]. Proponents assert that nuclear energy provides energy security at low carbon emissions, thus considering nuclear energy as prime for public benefit; opponents assert that nuclear energy risks radiation and the proliferation of weapons, that it is expensive and intrinsically requires an authoritarian power structure in society (to secure nuclear against sabotage). The IPCC is seen as sidestepping critical questioning of nuclear energy's supposed low-carbon profile [47], while lifecycle emissions associated with this fuel use remain contested [48–50].

A range of actors (from corporate, to state actors, NGOs and religious institutions) actively try to shift the discourses in which the energy transition is interpreted and negotiated, often through lobbyism. This refers to (embodied representatives of) organisations being subjected to affirmative or confrontative communication with the lobbyist (typically contracted agents). The same lobbied and lobbying organisation may navigate a range of agreements and disagreements. For instance, Greenpeace and the European Parliament's Greens might agree on energy consumption reduction policy to reduce emissions, but not on carbon capture and sequestration [51]. Lobbyism is highly contingent on access to specific individuals. So, individuals and their agencies matter. This includes their situated networks, or social capital. Individuals are key to just energy transition in several ways beyond lobbyism – for instance as doers (engineers, managers, developers, service agents [52]), as users of energy, as citizens with rights, as activists, and as ethical subjects, all coming with distinct situated knowledges of energy.

The study of infrastructure has conceptualised how such diverse actors and the institutions and organisations they are part of relate to and through energy infrastructure [53]. Relationships to energy vary based on space and place – a corporate boardroom, lab engineers developing an energy saving device, workers in a control room, drivers in fossil fuel vehicles. Many infrastructural relations and components, typically hidden for these actors, become visible only upon breakdown, when expectations are not met [54].

For instance, the energy meter is treated very differently by engineers, by corporations, and by different household members [55] – some measure electricity use, others control the amount of money spent on electricity, while others ignore it entirely. The introduction of smart meters changes existing energy relations. It opens and closes opportunities, in ways that may improve or undermine a household's agency over its energy consumption [56]. Results depend on whether control is devolved to users through sensory infrastructure in an intelligible manner, or whether automation increases centralised control and remote flows of data on energy use and pricing, controlled through invisible, complex, corporate-owned algorithms [57]. Physically, data and control over energy use flow through energy infrastructure; in a legal-regulatory sense, they are situationally governed through the political economy of institutional configurations.

2.2. The relationship between energy metrics and infrastructural change

The transition to low-carbon energy infrastructure has been shown to be interlinked with energy poverty [40,58]. Governing infrastructural change to achieve carbon-neutrality and alleviate energy poverty must be informed by evidence on synergies and how to avoid goal conflicts [58,59]. As a basic premise, energy policy should be informed by metrics [60,61]. Yet, the very metrics of energy poverty are contested [62,63]. Such contestation is rational given that metrological choices shape both the appropriate scale for governance and the manner in which institutions can or cannot steer infrastructural components and relations (see [64,65]). Stirling [41] shows how deeply knowledge and power are interwoven in energy infrastructure politics.

We draw on a broad literature to conceptualise how measurement, metrics and evidence are established and processed in practice. Sociologies of science-society relations highlight the role of converging and diverging evidence in shaping societal and expert discourse as well as decision-making for sustainable development [66,67]. In the context of discourses of evidence-based policy [68], it is highly relevant to note that while evidence can be enrolled as legitimatory capital [69], that very evidence may well be uncomfortable, and for that reason also ignored [70,71]; the tobacco and pharmaceutical industries provide notable examples linked with the suppression of clinical trial data [72].

The governance of environmental expertise has political consequences, can be socially exclusive or generate mistrust in knowledge infrastructures [73,74]. Datafying environments to integrate these into markets may be counterproductive, with unintended effects [75–77]. The same holds for socio-economic realities [78–80]. Simply put, digitalisation always implies users, learners and thus issues of digital literacy and socio-economic and demographic inequalities. Social studies of comparison, valuation and digitalisation indicate that new forms of datafication, calculating or designing algorithms can stabilise, and destabilise, societal and environmental ordering [81–83]. Not just since the advent of machine learning and other big data analytics, we can identify agency within the data/calculative infrastructure itself, with social and political effects [75,84,85]. Measuring things and turning these into data does not simply record realities but also affects these realities. We call the infrastructural-technical-political knot of practice that is part of shaping and bringing about realities an enactment. Enacting the phenomenon of energy poverty through metrics implies not only defining the dimensions and indicators of energy poverty, but also the practices of turning these metrics into action, database work, interviews, in a specific situated context, such as assessing the energy poverty of a household with a very specific and contingent combination of energy consuming devices, their heat generation and the influence of another record summer's warmth.

Contrary to popular technical discourse, operating metrics does not merely imply an ontological politics that defines measurement devices, indicators and data; it also involves an ontic politics, which is not necessarily determined by what the human and non-human agents have agreed to do but rather by what it is they actually do. Measuring something can involve consequential errors and unknown bias [81,86,87].

Governance for energy infrastructure change can and does attend to energy poverty metrics (consider the EU EP Observatory). DellaValle and Sareen [88] point to the limited availability of panel data on EP and the low awareness of EP among the energy poor as problems for tackling EP.

For governance to expand its attention, we can expect a process of negotiating and defining an ontology of each indicator. Given different data, different constructs of the energy poor are possible [34]. A critical question is who constructs the metrics. Which affected communities are involved in co-constructing such metrics? Moore [62] pushes us to consider substantively how indicators are constructed. For instance, he indicates that fuel poverty in England is defined in terms of fuel costs. That implies a conversion factor between costs and amount of fuel available. When temperatures are far off from the prescribed comfort temperature, then more fuel is needed to reach the comfort temperature. The administrative costs are higher when considering more fine-grained averages of costs/temperatures rather than one average per year. Similar data problems relate to data about the housing stock (see [89]). Here, administrators have a range of options to simplify their constructs about the energy poor, where each simplification comes with different qualities and quantities of winners/losers.

Beyond such clarifications, an attempt to understand how energy poverty is caused must also address how actors who shape energy infrastructures engage with uncertainties about the components and relations they are concerned with. The insight into such non-formalised practices requires a metrology that employs methods sensitive to the in situ work and conduct across the energy infrastructure, not just at the household level but also in the design and production of energy-saving and -consuming technologies.

With this conceptual foundation in place, we now turn to the operationalisation of an analytical framework that posits energy poverty as a policy oriented mobilisation of energy justice, for use in assessment of energy infrastructure transitions.

3. Theory: an analytical framework for assessment

This section presents an analytical framework subsequently put to use in the results section. The sub-sections on energy justice and on EP as its policy-oriented mobilisation provide an analytical framework that amalgamates classic understandings of energy justice (as distributive, procedural and recognition-based) and the EP metrology framework summarised above. We elaborate how energy transition scholars have established key aspects of justice to consider in shaping infrastructural changes. We then proceed to link these concerns to EP metrology, which is an essential step given the relationship between infrastructure and metrics. This section concludes by presenting an analytical framework that identifies how to co-shape EP metrics and low-carbon infrastructure transitions in a manner that advances energy justice by way of questions targeting forms of justice in these transitions.

3.1. Energy justice: distributive, procedural and recognition based

Energy justice broadly refers to the objective aptly captured by Sustainable Development Goal (SDG) 7, namely clean and affordable energy for all (see also [90,91]). This features multiple characteristics, which chiefly include accessibility (physically and in terms of affordability), reliability (temporally and in terms of stability), low-carbon emissions (for broader fairness by addressing the climate challenge which disproportionately impacts groups and individuals with higher exposure to climate risks) and inclusiveness (with a notable push to recognise energy as a basic human right in Europe and ensuring basic levels of energy access worldwide, cf. [30]) [57].

Scholars in the substantial community on sustainability transitions that works on socio-technical systems such as energy have brought insights from environmental justice to bear on the concept of energy justice. A range of recent notable contributions and collections ([28]; see also [92]) mobilise three core dimensions: energy justice as distributive, procedural and recognition-based, with others in addition. While variants include cosmopolitan justice [26] or emphasise spatial justice [93], the triumvirate is adequate for our purpose, to provide a framework that can help understand EP metrics in relation to energy infrastructure transitions, also mindful of questions of identity vis-à-vis justice as recognition. We thus operationalise definitions of the three dimensions broadly in keeping with Jenkins et al. [92] and the extensive literature reviewed therein.

Distributive justice pertains to how environmental benefits and burdens are allocated with regard to equity and responsibility. For instance, in relation to retail electricity systems, this implies ensuring that everyone can afford basic access to clean electricity in a convenient manner, rather than concentrating profits in the hands of a few large energy companies and limiting access to elite clients who can consume large amounts of electricity. Many such measures exist in electricity regulations, e.g. the principle of cross-subsidy through differentiated tariffs with progressive slab structures.

Procedural justice refers to the nature of involvement and influence of diverse stakeholders and energy subjects in decision-making as a mode of exercising citizenship over changes in key energy infrastructure. To take an example, mobility systems have undergone major transitions numerous times over the past century, with the involvement of various citizen groups to different extents. Twentieth century planning procedures often favoured car lobbies who were more organised, influential and better resourced than other, more dispersed and weaker interest groups. However, cities such as Copenhagen and Amsterdam have worked to build more just and inclusive procedures that go back to the 1970s, and proactively sought to include more diverse voices and concerns to inform mobility planning. The result is evident in recent shifts in their mobility systems away from car-centric infrastructure to more non-motorised and public mobility infrastructure.

Justice as recognition is concerned with the consideration of the degree of inclusion and linked nature of (mis)representation of sections of society, especially marginalised groups and identities shared by collectives characterised by difference to prevalent hegemonic norms with regard to intersecting inequalities. This recognition-based aspect of justice is crucial to secure inclusive and fair systems, particularly for highly vulnerable user groups along intersectional lines of gender, ethnicity, class, age and other forms of social identity [94]. This dimension tends to suffer relative neglect, perhaps due to its more abstract nature, but is nonetheless important [95]. For example, drawing on the case of urban built environments, there is a clear socio-spatial patterning to which neighbourhoods residents of particular income classes are typically able to afford to live in. These neighbourhoods have distinct building legacies that render some housing far less energy efficient, placing the burden of high energy bills on their residents. These typically overlap with low-income neighbourhoods [93]. If energy efficiency schemes that subsidise building retrofits can target such residents as a form of recognition-based justice, the effects of such subsidies are likely to be both more equitable and have greater efficacy in terms of carbon emission reductions.

3.2. Energy poverty as a policy-oriented mobilisation of energy justice

In the definitions of energy justice dimensions above, we have already used some instantiations that convey a sense of EP. Here, we specify a definition of energy poverty as a condition whereby people are unable to secure adequate levels of energy services in the home [3]. This framing has a legacy of having gained increasing and adaptive recognition in the UK and Ireland over several decades. During the 2010s, this effect became more palpable in several European countries, and has been encoded into many European Union member states' National Energy and Climate Plans 2030 since 2019 (authors' analysis of the plans; but see Bouzarovski et al. [96] and Roberts and Gauthier [97] for critical appraisals of quality of EP encoding in the plans' drafts), European Commission funded projects through Horizon 2020 calls [98] as well as the European energy poverty network ENGAGER [99] and more recently the European Energy Poverty Advisory Hub; these have been instrumental in accelerating cross-fertilisation and policy uptake in and beyond Europe.

While these are heartening developments, cutting-edge scholarship indicates the need for follow-up to ensure that policy appetite for EP alleviation actually advances an energy justice agenda. Scholars show that different aspects of EP are salient in not only different countries but at sub-national scales of regions and suburbs. For instance, thermal comfort requirements for cooling are increasingly important in Southern European countries [100], increasing penetration of electric mobility is changing dynamic electricity tariffs with potential adverse impacts for vulnerable energy users in several Nordic countries [101], and building energy efficiency improvements are a common need in many post-Communist contexts [102]. Thus, EP metrics must be contextualised to many diverse situations, and also reflect an understanding of the changing nature of energy infrastructure across sectors due to low-carbon transitions that increase the need for coordination across sectors.

This leads to the challenge of integrating energy justice dimensions with an understanding of EP metrology in a manner that invites critical and reflexive application to low-carbon energy infrastructure transitions across energy related sectors. Accordingly, we amalgamate the three energy justice dimensions and the three EP metrology axes (drawn from Fig. 1). We cross-tabulate:

- the three axes of EP metrology: shaping EP metrics (ensuring sensitivity to historical trajectory), enacting metrology (maximising coverage and accuracy), and reconfiguring metrics (mainstreaming innovative EP metrics); and
- the three energy justice dimensions: distributive, procedural and recognition-based justice.

The result is Table 1, a 3 × 3 justice-sensitive analytical matrix for scrutinising EP metrology in low-carbon energy infrastructure transitions. Within this matrix we provide sensitising questions, that are sufficiently openly and broadly framed to power empirical attention to heterogeneous contexts and identities.

In Section 4 (Results), we apply our analytical framework, informed by this matrix, to three schematic cases of energy infrastructure transitions in energy related sectors. This application develops and illustrates a sensibility for the EP metrics that are required in order to address the energy justice challenges that transitions give rise to.

4. Results: framework application to schematic cases in three sectors

The schematic cases we use to demonstrate framework application below capture a range of energy infrastructural sites whose evolution has impact on energy poverty alleviation. Framework application identifies aspects where clarity is required – through specific kinds of EP metrics that inform analysis, policy and implementation – in order for infrastructural change to advance energy poverty alleviation. Similar application to specific energy infrastructure transition cases can identify concrete steps forward to generate requisite EP metrics, e.g. by employing datasets collected at the urban or regional scale such as electricity disconnection event records. We show that the matrix can be applied in both ways, following the axis of EP metrology or the axis of justice.

Table 1

A justice matrix to problematise and scrutinise energy poverty metrology in low-carbon energy infrastructure transitions.

	Shaping EP metrics	Enacting metrology	Reconfiguring metrics
Distributive justice	How has (in)equity been framed in the metrics?	Who wins/loses in the design and deployment of EP metrics?	How can equity be inserted in EP metrics?
Procedural justice	Who is in-/excluded in defining EP metrics?	Who is in-/excluded in assessing EP?	How can inclusion be mainstreamed in EP metrics?
Recognition-based justice	Which contexts do definitions of EP metrics (not) take into account?	How context-aware is EP assessment?	How can EP metrics reflect contextual heterogeneity?

4.1. *Digitalisation of retail electricity – grid-to-home relation*

The hegemonic discourse of digitalising retail electricity infrastructure expects thorough “smartification” – a smart grid, city, home, and in that home smart technologies/devices. To power that smartness, for instance the EU has provided regulation to deploy smart meters across the union (EU Directive 2019/944). These smart “solutions” are supposed to be tightly interwoven. Here we focus on the grid and its relationship with the home, leaving aside broader themes like the potential regressive effects of dynamic tariffs across households' socio-economic status (but see [103]). We acknowledge that several energy efficiency measures are publicly financed, e.g. light emitting diodes for low-electricity public lighting, and may not directly burden but rather benefit households. Focusing on the household, the smart home is foremost presented as activating the customer. That activation is supposedly driven by digital information provided via in-home displays, mobile displays (apps on smartphones) and the smart meter itself. The data provides the evidence to turn the customer into an informed user of electricity, a user that can take evidence-based decisions and rationally assess evidence to optimise the household's energy consumption. With this information, the user is presented as an actor who learns how to deploy electricity and electricity consuming devices in a way that simultaneously saves energy. In this narrative, the user also achieves greening and is turned by virtue of smart electricity consumption into a responsible, green citizen.

The grid is expected to shift from being steered by demand to being steered by supply. In the grid, multiple – also small-scale – renewable energy sources (wind, solar) are to provide decarbonised energy. Local electricity storage can provide electricity on demand. This “flexible grid” requires intelligent load balancing. Smart homes function in this imaginary as smart consumers that serve to stabilise the grid. This effective smart grid then is imagined to save the need for massive investment in capital-intensive large-scale transmission infrastructure.

The distributional effects of these smart solutions come with a range of implications; we set out from political-economic and carbon effects. First, acquiring smart home technologies (SHTs) is expensive. To make such investments pay off, the SHTs need to be used intensely. However, if the user minimises use, the investment in SHTs may never pay off [104]. The more SHTs including manifold smart sensors of the home are used, the more data is generated that calls for, and invites innovation for, analysis. This increase in data results in increased computational demand, that can be expected to increase energy and hardware consumption, and thus extraction of rare earths and water, and increased global warming [105–107]. Those who lose as part of this material political economy of data are not yet considered in enactments of EP metrics. Any reconfiguration of EP metrics could attend to such situatedness of data in friction with environmental sustainability and the distribution of local and global effects.

Further distributional effects concern which users fit well into the smart infrastructural relations. For the user to interface well and ubiquitously with the smart home, the user has to be equipped with an up-to-date smartphone/computer. However, not all home dwellers are equipped with up-to-date smartphones, or are socio-culturally positioned to realise the technical capacities whose presumption shapes EP metrics. For the user to be able to optimally time the use of SHTs, the user has to be flexible enough with their organisation of time. For instance, the combination of a smart tariff and a smart laundry might suggest washing at 2 am in the night; but at that time dwellers, such as shift workers, might not be home and awake to take care in case of an accident (and an insurance might not cover the damage, which can exacerbate social inequality and vulnerability by way of (re)distributing financial risks (cf. [108])), or conversely, somebody might have to sleep next to the laundry, lowering the quality of sleep. Temporal flexibility is societally unequally distributed, correlating with class and gender [109,110]. Reconfiguring EP metrics can be supported by considering the studies of the use of SHTs in real-life that indicate that the users of

SHTs are well identifiable in terms of age and gender – they are likely to be male and below 55 years old [104].

Significant interest in SHTs exists within industry. SHTs' capacity to generate data about the home promises new forms of intelligence (which is contested societally in terms of surveillance [111]). The users of the intelligence (that is the data platforms) profit from the new data, and the producers of the data (the electricity users) are unlikely to be compensated for their transparency [112] about their electric selves (by which we refer to the quality and quantity of energy production and consumption that characterises the electricity user), without recourse to courts, where access is regressively distributed in society due to associated burdens of risk, financial cost, time and navigating bureaucracy. Standards need to anticipate electric fingerprinting [113,114]. Further possibilities of use and reuse of data can be expected to be generated by platforms. Further, these can be expected to increase socio-economic inequalities [115]. At the same time, surveillance will not be perfect; the range of smart devices and IoT can be expected to generate new vulnerabilities – security risks, risks of hacking/cyber crime and policing measures, and potentially new forms of data privacy infringements and data leakages. This ties in with additional emergent distributional risks of SHTs.

Procedurally, assessing the smart grid's, smart homes' and SHTs' users requires clarifying who or what that user is. An initial difficult decision concerns whom to consider a key actor as using the smart home/grid [116]: is it what national authorities consider the final customer or is it the grid operator or another infrastructural agent who has an interest in SHTs as performing balancing work? Consider the final customer: if they have a smart meter in their household, but do not engage with it, is that customer then considered a (smart) user? In terms of recognition, the smart home dweller can be expected to change over time. SHTs are reported to alter users' comfort expectations [117], which may well relate to social identity, resulting in increasing costs and emissions, thus requiring EP metrics to represent increasing financial vulnerability of the SHT user. Such individual changes of comfort expectations can spread socially, establishing new conventions, shared norms of comfort.

Procedurally, it is key to go beyond the individualist methodology and recognise energy use that is co-constructed in a socio-technical world, in which agency is distributed across humans and non-human participants. For instance, Lovell et al. [56] report data visualisations to be hidden in some SHTs, where the SHT's cover performs the hiding, with that hiding configured by a designer, who may well have considered themselves as the user [118], instead of analysing actual user needs in the "real world". Another way in which the individualised household/user is problematic concerns the power relations between the household's tech savvy agents (typically male) and other occupants. We can expect existing inequalities in the household to be partially alleviated, partially aggravated – will device controllers manage distribution of energy resources (as a form of financial resources) within the household, thus exercising power, gendered or otherwise (cf. [119,120]; see also [121])? Finally, we need to consider whether users are processed as customers or as citizens. If SDG 7 gets close to asserting rights to clean energy access and a level of comfortable energy services, then the construct of users as customers becomes questionable.

The recognition-based justice dimension draws attention to the imagined user in the smart home, who is typically drawn in an utterly unrealistic way: The user comes with quite complete information and wants to decide rationally, is "utility maximising and technologically literate" ([104]: 69). Against this imagination, Sovacool and Furszyfer Del Rio [122] summarise studies that indicate that the user has to learn significantly to be able to use SHTs well. One complexity that challenges smart home/grid learners is that the boundary of what is inside the home and outside is not stable, as the smart home is infrastructurally influencing and influenced by technical apparatuses in the home's environment, within the grid [56]. DellaValle and Sareen [88] point to possibilities and challenges of teaching users about statistics, which they consider relevant to individuals acting against EP. As it cannot be assumed that all users are equally capable of EP-relevant learning, the contextualisation of the user needs to contain facilitators of learning or translation. Nyberg [123] suggests that SHTs tailor information, while Lovell et al. [56] point to energy advisors who support citizens (and non-citizens) in the use of SHTs. However, the capability to learn about digital technologies is socially unequally distributed [124,125]. Even if a cost and energy saving technology is presented as such to users, the user may not act according to the rational actor imaginary, but can be expected to be behaviourally complex, socio-technically configured as well as culturally positioned (see Eurofound [126] for a discussion of home occupants' declining cost-saving from renewable energy solutions).

Existing research on metrics and smart grids/homes is widely silent on whether users consider information and analytic services helpful, and on how such digital services are actually used, empowering or disempowering occupants. We require information on what support users draw on to learn about SHTs. Broadly, to assess the EP risks of smart homes/grid, in-depth studies of SHTs use within the household as well as of the use of data by the SHT are needed (how does the intelligence translate back into e.g. financial firms that limit access to credits, generating for instance new risks of energy (data)-induced poverty?). While we cannot offer detailed treatment here, general principles worth highlighting include privacy-by-design, default primacy of open source solutions, and the minimisation of data collection (see also [127]).

4.2. *Diffusion of electric vehicles*

The electrification of mobility is presented as a vital aspect of low-carbon energy transitions, as fossil fuel vehicles emit approximately a fifth of greenhouse gas emissions. For low-carbon infrastructure to result, it is key that electrifying transport is grounded in decarbonising electricity through massive solar, wind and hydro power; electric mobility is more efficient than internal combustion engines [128]. Public and non-motorised transport present further ways to reduce energy demand linked with mobility. The issue of ownership models of transport devices is out of scope in this paper (for a problematisation of car-sharing, see [129,130], for an optimistic view [131]). Yet inducing shifts from fossil fuel to electric vehicles in itself is complex.

Thus far, policy support for electric vehicles has typically secured individual car-centred transport ideology and infrastructures, called "automobility" (see [132,133]). This electric vehicle-based automobility not only alleviates relative emissions [134], it also reproduces other problems associated with car-centred mobility [135]. Automobility has direct effects – it costs the households, generating debt and vulnerability [136–139]; it costs the public, whereas walking and cycling represents public benefits [140]; motorised road traffic generates a range of emissions [141]; health benefits of bicycling exceed its risks in the urban environment [142]; and cars as culturally significant markers mediate and partially strengthen socio-cultural inequalities [143]. Furthermore, automobility has indirect effects, e.g. traffic accidents, which can severely injure, disable and kill people and impose costs and loss of income on households. E-mobility research features limited attention to bicycling [144]; and e-mobility normalises the use of electricity for transport (thus generating e-velomobility, see [145]), with the associated environmental, social and justice effects of battery industries – not only emissions of GHGs [146], but also pollution at sites of mining, production, recycling and disposal [147,148], reproducing an extractivist order [149,150]. In short, car-centred electric vehicle policy can maintain the normalisation of automobility with cultural and socio-economic consequences of exacerbating existing inequalities and marginalising vulnerable population groups that are typically less vocal [136,151].

In terms of shaping metrics, we examine inequity in EP metrics. A focus on transport EP has emerged [152] and uses innovative data through e.g. travel smart cards [153]. Car sales in Europe look to be reducing while public transport options have increased [154], which signals a move towards equity, but in Norway with the highest electrification of automobility, overall car ownership has barely declined [151]. Rather, public debate in this context has focused on exclusion of suburban drivers in urban planning interventions such as congestion fees [155]. This begs the procedural question of which voices are excluded, namely those of less organised groups than automobile lobbies [151]. In reconfiguring EP metrics, there is thus a need to acknowledge contexts such as suburbs with different spatial needs than city centres, and to consider mobility patterns and public transport offerings to reduce car dependence. This requires urban and regional transport planners to embrace metrics that convey a clear picture of transport EP [156].

With regard to enacting metrology, the built environment of car-centric urban form favours privileged economic classes and has enshrined and normalised in public space provision a large "motor-print", with a car at 0 km/h requiring 10 times more space than a bicycle, and a car at 50 km/h requiring 70 times more than a cyclist [157]. In that analysis, metrology should understand space both in terms of road space distribution and as a function of speed, requiring a mapping of speed zones to assess fair transport distribution. Distributed metrical collection examples include monitoring bicycle usage on dedicated lanes in cities like Copenhagen and providing multiple ticket fare calculation modalities (per trip, per distance, specific commutes and zones) in cities like Amsterdam. Comparing these metrics with car ownership and use rates as well as proxies like city-centre parking spaces can help cities move towards fairer public mobility while electrifying buses and increasing electric solutions like light rails and subways. Increasingly, car-free zoning is a popular urban intervention, prominently in Paris with its €225 million investment to turn Champs-Elysees into a car-free garden. To reconfigure EP metrics, spatial metrics should consider the range of actors that are involved in selecting sites. Does this investment benefit the energy poor, or could a similar sum deployed in suburban Paris have created more value for those who live in modest neighbourhoods?

By way of reconfiguring metrics, we consider how to attune EP metrics to capture equity concerns. A measure could be transport related energy consumption – planners could aim to reduce the required energy demand for everyday trips through adequate provision of low-carbon public transport services, including shared mobility solutions, and by offering low fares up to a basic minimum level of transport energy use. By contrast, excess transport energy use through car usage could be taxed. Yet such measures require a baseline for which new metrics must be mainstreamed through systematic collection of transport energy data. With electrification and digitisation, this is easier than before, as it becomes possible to monitor individual car charging and public transport trips in real-time (with privacy complications discussed by Kitchin [158]; and privacy solutions emerging, see Xie et al. [159]; Fuxjaeger et al. [160]). This opens avenues to mainstream inclusion by implementing incentives and penalties across entire populations to alleviate transport EP while penalising consumerist behaviour that uses unfairly high transport energy (for instance via occupancy-adjusted tolls and dynamic charging tariffs, coupled with material advantages for selected target groups consistent with principles of affirmative action). Lastly, we consider how to reflect contextual heterogeneity in such analyses, for instance for remote rural residents in a region [161]. Here, demographic metrics could inform public provision of car-sharing schemes, already popular through private companies in many parts of Europe. This would, in turn, generate usage data that could be used to inform metrics to improve the service.

This analysis can be translated in concrete questions such as asking households how they perceive transport options, with the option to identify transport option poverty as a form of energy poverty. Beyond investigating the organisations involved in transport policy making and implementation, it matters to mobilise and access the critical expertise of transport planners about the inequalities that they know are strengthened (or alleviated) even if their employers, the organisations, do not want to locally implement that expertise.

4.3. Energy efficiency measures in the built environment

A key element of low-carbon energy transitions relates to the most ubiquitous of infrastructure, namely the built environment. Energy efficiency retrofits can create huge reduction in energy demand [162] and alleviate EP through improved thermal comfort [100]. Within the distributive justice dimension, we note, however, that targeting retrofit schemes is notoriously difficult, with higher educated and better resourced actors (e.g. rich households) more likely to access benefits [163]; although, the benefit scheme may be designed and implemented pro-actively to secure take-up [164]. Yet, such design has to consider the structural limitations given for instance by actors that do not or cannot expect to occupy a built infrastructure for a sufficient duration for the retrofit to be perceived as efficient (e.g. a retrofit that pays off after 10 years, but the occupant expects to move away within that time; consider the inclusion and information of stakeholders, [165–167]). Moreover, countries have diverse legislative bases, meaning that aspects such as mould that would be recognised in Denmark as a basis for home insulation against damp by a dedicated ombudsman are less likely to be recognised in another context such as France without a dedicated mechanism [168].

In terms of shaping EP metrics with regard to such infrastructural change, our framework directs attention to where distributional justice might be overlooked, e.g. in providing households subsidies for rooftop solar energy modules to lower electricity bills. Techno-economic models *routinely* favour incumbent electricity distribution companies, making it unattractive for households to make such investments, even though they stand to benefit over time. Poor households cannot afford capital outlay with recovery over years. EP metrics that make households below a certain income level eligible for low-interest loans for rooftop solar investment could improve targeting. Procedurally, we note that yet other categories such as tenant households are excluded by definition due to inability to make major changes to their rooftop. Here, investment into a "virtual solar" plant in community energy projects (e.g. virtually combining photovoltaic elements on the public-school roof and on private roofs) could be incentivised for such households through granular income metrics. Such income metrics exist but are rarely employed in relation to energy efficiency measures in a systematic manner, due to inadequate accounting for the elite context of small-scale solar projects.

With regard to enacting metrology, our framework guides us to the distributional dimension, identifying winners and losers in energy efficiency scheme design and deployment. For instance, are schemes relatively easy to access for energy vulnerable actors, or those without a high level of education, and is information widely disseminated to ensure that a range of actors can benefit? Procedurally, metrics on the range of income, ethnicity, residential location, age of beneficiaries and ownership mode could provide a check against concentration of benefits among a small range of actors, with e.g. quotas and incentives for subsidies that are targeted to retired people, single-parent households or tenants. The failure to add such criteria and to identify them as shortcomings even after scheme deployment may be a reflection of narrow viewpoints in assessment protocols, perhaps as an artefact of inputs from too homogenous actors not equipped with a range of lived experiences. Thus, we see a need for context-aware assessment, where e.g. localised criteria are included in monitoring of implementation. For instance, in Bucharest the district heating network is aged and often provides lower heat quantum along some streets and to houses located towards the end; such households could be prioritised for support from retrofit schemes. Here it is worth cautioning against a narrow focus on energy poverty alleviation, as cross-sectoral concerns come into play: for instance, home insulation must be accompanied by adequate air circulation standards to prevent risks like radon accumulation.

By way of configuring metrics, we can extend this example. In the absence of adequate metrics to capture differences in service delivery, residents made their own open access map layer, where the (non)performance of district heating is crowd-sourced, providing a democratic metric on users' thermal status. This is an instance of inserting the distributional dimension in EP metrics and may on occasion be appropriate to locate at the urban scale rather than in elaborate national databases. How can the inclusion of such EP metrics across scales and on diverse aspects of EP be mainstreamed? This question prompts us to consider what the appropriate scale of actor may be to act on certain forms of EP. In Barcelona, electricity disconnection data can serve as a good proxy to identify EP households. Moreover, civil society actors have been facilitating inclusion of EP households through help in filling out applications to retrofit schemes, a self-selection mechanism possible at lower spatial scales. With a move to dynamic tariffs, there is a need for targeted safeguards against high time-of-use tariffs being imposed on vulnerable users with inflexible energy needs who may not benefit from the affordances of automated energy flexibility. Lastly, how can such metrics reflect contextual heterogeneity, even when scaled out across cities? It is possible to develop building typologies at sub-national scales such as parishes and regions, which can ease identification of neighbourhoods and blocks that are likely to have higher EP incidence. Post-Communist contexts display such socio-spatial patterning [102,169,170], and it is moreover possible to draw on innovative data sources like building energy certificates and smart electric meter data to complement such typologies.

5. Discussion

Energy infrastructure evolution is mediated by the political economy of a historically top-down structured energy system that cuts across sectors such as electricity distribution, mobility and the built environment. This conditions the dynamics of low-carbon transitions in ways that depart from both the new techno-economic competitiveness of renewable energy sources and from the urgent social concern of energy poverty alleviation.

However, when reviewing supposedly low-carbon energy solutions – digitisation of retail electricity, the diffusion of electric vehicles in the mobility sector, and energy efficiency measures in the built environment – we identify cause for concern, too. Investigating the political-economic dimension of these infrastructural trajectories makes available the theme of how power and privilege can be (re)produced in these infrastructural relations.

Households that are able to invest in such new infrastructures (acquiring, for instance, SHTs, energy storage, wind and solar energy generators, or individual electric vehicles) are positioned to better exploit support schemes for green technologies and profit from energy savings these technologies might effect. Households with high energy consumption and prosumption (e.g. selling rooftop solar electricity back to the grid at strategic high-tariff periods) may be able to use SHTs efficiently as they stand to make non-negligible gains from increased efficiency and arbitraging the grid by providing energy flexibility. By contrast, households that are already minimising energy consumption might be induced to increase their absolute energy consumption by the SHTs, due to low time-of-use dynamic tariffs and nudges built into user interfaces. This is financially relevant, aggravating poverty, and environmentally relevant, increasing energy consumption. The focus on car-centred electric vehicles, further, can sidetrack from the needed transition to a sustainable mobility infrastructure, and can maintain and even further limit transport options for households who cannot access expensive individually owned electric vehicles.

The expected SHTs' and smart cars' data-based control capacities give rise to two further political-economic challenges. First, within the household, the smart green technologies risk being enrolled to maintain or aggravate intra-household political-economic relations, such as constraining access to the technologies' (energy) services. Second, in the relationship between the household and its occupants (whose lifeworld can get datafied via the SHTs) on the one hand, and external data analytics and brokerage platforms on the other hand, platforms can generate new forms of exploiting the newly-visible electric selves.

The range of novel technologies themselves come with environmental consequences, being constructed with, for instance, rare earths, and other resources accumulated in extractivist regimes often in the Global South. Missing are life cycle analyses (LCAs) with a scope that includes the production chain. However, beyond what LCAs can make transparent, these extractivist regimes risk aggravating environmental crises and increasing global poverty, undermining EU objectives about global poverty reduction. European metrics of poverty could well consider accounting for poverty effects caused by European consumption of SHTs and other devices that power the European Green Deal.

This application of the political-economic sensibility generates an insight into the justice effects of low carbon transition infrastructures. Our analysis resonates with cutting-edge research on injustices of low-carbon energy transitions which have been amassed through detailed listings that draw on extant literature across a range of diverse energy infrastructure cases [26].

We continue with this normative premise: Explicit awareness of these political biases must inform transition approaches by specifically developing systems of checks and balances to ensure distributive justice (so that energy infrastructure transitions benefit energy citizens, including inhabitants without rights that flow from legal citizenship but who nonetheless have a right to access adequate energy services, i.e. to not experience energy poverty), procedural justice (so that energy citizens are involved in providing a baseline of their actual needs and visions of low-carbon energy futures) and recognition-based justice (so that typically marginalised groups are adequately represented in terms of their diverse needs, desires and contexts).

Because energy infrastructure decisions take place at a variety of scales and in spatially dispersed ways, the metrics that inform these decisions must be analysed and situated at multiple scales and with context sensitivity across this vast range of circumstances as well: rural/sub-urban/urban, remote/proximate/intra-household, national/regional/urban/local. Not all of these are equally easy to generate metrics for, but the digitisation of energy infrastructure provides an opening to change this materially contingent artefact and thereby also the social basis for assessment. That is to say, explicitly inclusive energy policy can secure a win for justice outcomes rather than being guided by innate tendencies of infrastructure (cf. [10]) and by dominant interests [7,13] to direct what is measured at what point. Metrics are socio-technically constructed, and unless this construction is explicitly directed to secure more just outcomes, it risks entrenching existing inequalities and misrecognition of energy citizens for decades ahead, beyond urgent transition timeframes.

Such a basis in progressive applied visions of energy justice must be backed by cognitive-cultural shifts in wider societal understandings of energy transitions that are reflected in key policy decisions. With respect to EP, such a shift seems underway in both the policy and public sphere, although with perhaps the former moving ahead of the latter. Analytical efforts have been geared towards providing baselines from existing metrics, but we discern a need to address where metrics have gaps or biases against the baseline of energy justice (and more tangibly energy poverty alleviation). The application of our conceptual framework to the three schematic cases provides both specific and generic insights that suggest value in applying it to specific instances in diverse energy infrastructure related sectors to identify and ameliorate conflicts and vulnerabilities.

Distributive justice: The path to an equitable and just low-carbon energy transition is about framing an accessible, reliable, and fair transition across a cross-section of users and infrastructures.

The ability to obtain the service in SHTs, for instance, presupposes an informed user with the agency to actively monitor and adjust the devices to optimise the household's energy consumption. The challenge here is how to extend the metrics to include non-smart and marginalised users.

Similarly, in the case of electric vehicles, it is significant to go beyond the framing of the problem around urban, private car dependency, so that public transport alternatives and unorganised commuters who might be living in modest neighbourhoods are also equally enrolled in the collective sense of distributive justice. In the case of built environment, the capital-intensive nature of infrastructural changes, leading to energy efficient measures, systemically privileges educated and better resourced users. The challenge in reconfiguring metrics here is about how to include poor households and areas that are currently disadvantaged so that access to basic infrastructure is fairly and evenly distributed.

This matrix provides a systematic framework to extend the framing of inclusiveness and to identify risks wherein varied users and participants can be equally enrolled in the collective sense of distributive justice. In terms of distributive justice, we highlight a need for the elaboration and widespread deployment of EP metrics across multiple scales that are specifically sensitive to such sorts of unequal distribution of gains and burdens (including of risks), which can aggravate EP.

Procedural justice: This form of justice involves broadening the inclusion of various interest groups, especially those who are not enrolled as part of the definition and assessment to ensure greater energy equity.

When the SHTs presuppose an active usage of a new set of infrastructural relations, EP metrics development needs to engage with the diverse userbase including the vulnerable social groups who lack the technological literacy, capital and corresponding or supplementary devices and networks, including missing the cultural capacity to take advantage of supposedly empowering technologies. Similarly, this development process needs to carefully avoid car-centred discursive framings to ensure a process of metrics development that does not further privilege electric mobility that primarily focuses on urban, private transport as central to low-carbon transition at the expense of public transport energy options and involving remote or rural dwellers. In similar vein, the design of EP metrics needs to accommodate vulnerable economic and social groups in the construction of baseline assessments, which promises sensitivity to social and economic inequalities built into environments and housing infrastructure, in order to inform the design and deployment of energy efficiency schemes.

Using this matrix, sensitive to varied concerns of diverse, including marginalised, users, can bring about more accuracy and effectiveness across scales to the functioning of the system and its sustainable stability. In terms of procedural justice, we highlight a need for identifying and involving different socio-economically positioned interested groups at each scale within the EP metrics design processes.

Recognition-based justice: Any attempt to ensure energy justice is necessarily required to be sensitive about the overall environmental, economic and social context and range of identities of actors within which specific energy infrastructural relations are situated. Since the effects and risks of climate change on different sections of the population are disproportionate, an inclusive low-carbon transition needs to include those interconnected factors and acknowledge diverse identities to ensure fairness.

Across the three schematic cases, interconnectivity of systemic contexts inherently differentiates the agency of the smart, privileged users from those unskilled and unprivileged due to complex situated characteristics and social differences. Contextual heterogeneity also requires engaging with broader issues like geographical scale disparities, pre-existing infrastructure or economic imbalances, digital surveillance and negotiations of privacy. A justice matrix also needs to take into account those who are not part of the system but still may bear the consequence of technologically advanced, capital intensive, mainstream development. Furthermore, it has to take into consideration systemic and operational leakages during functioning, in terms of who bears the cost of the unintended consequences.

The matrix allows contextualising and engaging with systemic and structural inequalities that exist among energy citizens, and also makes space to accommodate the externalities and unintended consequences of low-carbon energy transition. In terms of recognition-based justice, we highlight a need for EP metrics design to consider multiple contexts, including the spatial and temporal contexts as well as the digital context that involves not only data and algorithms located within the energy infrastructure itself but also those sites of data analysis and reuse outside of the energy infrastructure, such as general digital platforms and financial services providers.

The three identified schematic cases – smart digitised retail electricity, mobility transition through electric vehicles, and low-carbon transition in the built environment – open up different locations and relationships where energy justice is negotiated. The agency of diverse individual users, distributed infrastructures, and financial and fiscal as well as policy restructuring are the primary sites where the translation of justice is located and negotiated. The justice matrix we propose provides an overall framework to extend the notion of efficiency beyond very situated tools and practices to accommodate actors at risk of EP in a more systemic manner, so as to build a just, robust and sustainable energy transition.

6. Conclusion

This paper identifies a clear need for a conceptual underpinning to inform policy decisions on changing energy infrastructure and energy poverty alleviation, notably in relation to the implications for what metrics require greater attention and at which scales. We emphasise the intertwined nature of the twin transition to more digitised energy infrastructure and climate neutral economies. We argue that to enable such a virtuous cycle, and safeguard against a vicious one, policymakers must understand energy infrastructure and metrics as two sides of the same coin, and address both in a manner that ensures a just transition, one that can alleviate energy poverty even as it enables low-carbon energy futures. Such innovated and reconfigured metrics need to be mainstreamed across policy institutions and sectors [4].

Improved metrics to support alleviation of EP within the transition to a low-carbon economy entail recognition of the historical legacy of energy infrastructure. The nature of energy infrastructure transitions is cross-sectoral but the metrics currently used to track it tend to be sector-specific. The changing socio-technical nature of energy and how it is related to entrenching poverty [31] remains inadequately accounted for at present: emergent energy infrastructural developments in the digital economy are relatively uninformed by EP considerations as they play out in primarily technology-savvy bubbles at the expense of broader deliberation and inclusion of relatively marginalised worldviews and concerns of the energy poor [171]. The novel digital presence of energy profiles enabled by surveillance of mobility patterns (through digitalised flows of personal mobility) and SHT usage establish new data risks. These (re)uses of data, for instance by credit platforms and data brokers, drive new forms of economic exclusion, that can cause poverty. The space for new data markets premised on the extraction and analysis of electric selves appears to be set to power new cycles of resource extraction and waste disposal, with attendant detrimental environmental effects. Both the new data risks and intensified resource extraction to power smart energy 'solutions' may well aggravate poverty in Europe and globally.

The transition to low-carbon energy infrastructures generates both direct and indirect EP risks. While direct EP has already been well recognised by policy and scholarship, indirect EP risks challenge the existing literature. Examples for such indirect EP effects are: the perpetuation of an (electric) automobility regime that privileges individual ownership of cars, risking poverty and vulnerabilities caused via the physical risk that accompanies individualised mobility forms through traffic accidents, especially victimising non-motorised transport users; and the poverty and novel vulnerabilities caused by economic exclusion that are likely to result from data reuse by financial services providers and other platforms within the digital economy that can access data about the (non)smart users [127].

Thus, to measure EP, EP risks need to be identified at multiple scales and across sectors and infrastructural relations. Towards this, a) some data sources and metrics already exist and are employed in assessments of EP; b) other data sources exist but are under-utilised, ostensibly due to a scale mismatch in institutional structures and processes of assessment [34]; c) other relevant data sources are not systematically captured at present; and d) the situatedness of data in socio-technical contexts needs to be rendered explicit within metadata of datasets to power reflexive and critical adoption of existing and emerging data sources or sets. The case of thermal comfort [100] and its intimate entanglement with differentiated identities and needs illustrates the complexity and necessity of requisite measures.

Already existing data sources that are not yet used across relevant scales and resolutions include, e.g., crowd-sourced grid heating maps (district scale), building energy certificates and typologies (block and building scale), and real-time retail electricity use and disconnections data (household scale). This category refers to data that is produced, for instance as a consequence of data-driven governance discourses (see [172]), but is not fully mobilised through joined-up EP policy, for instance urban EP metrics that are not mobilised in national-level analyses.

A significant body of data relevant for understanding the drivers and path dependency of EP in the changing energy infrastructure is located in the human bodies of experts. Like other agents of ecological modernisation engaged in the situated management of environmental transitions [52], experts of energy infrastructure hold deep knowledge about how their specific infrastructural sites (the components and relations their work engages with) can alleviate or aggravate energy poverty and other social justice dimensions. However, the dominant trend in scholarship is to address these experts by mobilising them as representatives of institutions, such as members of a governmental authority, an energy grid operator, or an energy solutions provider to end-users. This dominant tendency is unable to mobilise the deep and situated knowledges of these experts [33] because they are not mandated to share that knowledge. Instead of addressing these institutions, we see productive scope for research strategies that mobilise such experts' deep knowledge by approaching them laterally as embodied and situated informants and actors (see [173,174]) who co-shape the infrastructural and institutional relations that underlie EP. This research strategy can mobilise actionable knowledge during urgent policy windows of opportunity (see [175,176]).

For instance, most European member states explicitly mention energy poverty alleviation as an objective of their National Energy and Climate Plans 2030 (see https://ec.europa.eu/energy/topics/energy-strategy/national-energyclimate-plans_en). These can produce and integrate EP metrics across sectors and scales, making use of new coordination possibilities opened up through digitalisation of energy infrastructure, e.g. smart electric meters and monitoring hubs, smart devices including rooftop solar modules and digital building energy certificates. Policy workers have a leading role to play here by defining standards rather than letting these lag innovation. It is only through such proactive efforts that just energy outcomes can be assessed and secured with relevant metrics to inform policy for targeted EP alleviation.

Specifically for EP metrics, analyses can be conducted by public administrations as well as by citizen projects to inform cross-sectoral coordination. This is in keeping with a broader push to make energy and EP data openly available to enable complementary analyses that strengthen the democratic discourse on socioeconomic justice and low-carbon energy transitions (e.g. [177]). Thus, we close with a call to prioritise the key policy task of mainstreaming innovative metrics that can address EP across multiple scales and resolutions across energy related sectors and infrastructures. Compared to a major review on the political economy of EP a decade ago [53], we note that there is growing recognition of and coordination in support of this trajectory.

Declaration of competing interest

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

Data availability

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

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