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Decision-making and scalar biases in solar photovoltaics roll-out

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Rapid roll-out of solar photovoltaic (PV) energy is a key component of decarbonising energy systems. Yet clear risks are involved, including footprints from land use and infrastructure as well as socio-economic inequalities. Where are the critical decisions about solar roll-out made, by whom, and to what effect for justice? The paper reviews and synthesises emerging scholarship on solar PV roll-out, cross-sectoral aspects of this multi-scalar energy transition, and energy justice. We identify a trend of diverse scalar biases, and highlight considerable emerging research on risks of scalar injustice and the policy adjustments required to avoid them during rapid solar roll-out.

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Introduction

Rapid roll-out of solar photovoltaic (PV) energy is a key component of decarbonising energy systems for climate change mitigation. Because of the experience curve, technological innovation and economies of scale, costs fell dramatically during the 2010s [1]. In 2020, PV plants are cost-competitive in large parts of the world, and constitute a substantial, increasing share of annually installed global energy sources. This shift is reflected in academic literature on diffusion of this technology: the primary focus is no longer economic feasibility, it is ‘economic, political and social concerns including job transitions, stranded economic assets and geopolitical shifts driven by energy and related disruptions’ [2].

Decisions concerning socio-cultural and political economic aspects of solar PV roll-out are thus of increasing importance for climate change mitigation. Indeed, [3] argues that ‘understanding and adapting technologies and decision-making processes to a particular place and people will become increasingly important for the successful deployment of new energy technologies’. Correspondingly, our review asks: Where are the critical decisions about solar roll-out governance made, by whom, and to what effect for justice? By decision-making, we refer to the active use of judgement and/or authority in open-ended situations (cf. [4]), specific to the solar PV roll-out domain across scales of deployment.

First, we review and draw lessons from this scholarship (Section 2: Scoping review), identifying a variety of scalar biases and drivers based on richly contextualised studies of decision-making in solar PV roll-out governance. Thereafter (Section 3: Theoretical review), we probe how current configurations and political economic trends in decision-making impact scalar aspects of solar roll-out and its energy justice outcomes. Here we analyse state-of-the-art scholarship for insights on energy justice, scale, and the need to balance speed and social inclusion. The decision-making drivers unearthed in research should guide future solar PV roll-out by informing timely multi-level energy policy adjustments that pre-empt or address identified risks of scalar injustice. In closing (Section 4: Conclusion), we argue that adequate consideration of scale and justice effects is vital in order to ensure that governance decisions to implement energy transition strategies gather strong and enduring political constituencies.

Scoping review: sites and actors in decision-making for solar PV roll-out

We reviewed literature on decision-making in solar PV roll-out published during 2018–2020. This review drew on our domain expertise from research on the governance of solar energy transitions, and our background as human geographers with a focus on scale and power dynamics. Within recently burgeoning scholarship on solar PV roll-out, we shortlisted cited references based on relevance to actors (e.g. policymakers, energy regulators, solar developers, energy companies and cooperatives) and sites of decision-making at multiple scales across diverse contexts. In other words, we eschewed techno-economic studies of resource assessment and integration with other energy sources. Our focus was on roll-out governance, which we understand as the ‘political and social practice

dimensions of the diffusion of sustainable energy technologies' [5: 128], specific to solar PV.

A large share (20 out of 54) of the articles selected based on clear thematic relevance to solar PV roll-out governance were published in *Energy Research & Social Science*, with a further 3–5 each from *Energy Policy*, *Environmental Innovation and Societal Transitions*, *Renewable and Sustainable Energy Reviews*, and *Renewable Energy*. Our review drew widely, featuring articles from other energy studies platforms (*Nature Energy*, *Energy Sources Part B*, *Energy Strategy Reviews*, *Energy and Buildings*, *Energy*, *Applied Energy*, *Renewable Energy Focus*) as well as journals in technology studies (*Journal of Cleaner Production*, *Technology Analysis and Strategic Management*), environmental governance (*Land Use Policy*, *Environmental Politics*), and human geography and development studies (*Geoforum*, *World Development*, *Local Environment*, *Journal of Environment and Development*). This diverse representation is notable; it indicates widespread interest in the governance of a technology that has gained global significance and affects multiple sectors.

The literature reveals three trends associated with decision-making in solar roll-out:

- (i) The debate on solar PV roll-out has evolved from earlier conversations on economic feasibility to analyses of transition pathways and dynamics at multiple scales [6–9]. These analyses increasingly emphasise contextual specificities, such as socio-cultural energy practices [10] socio-political dynamics [10–12], innovation environments [13,14] and public attitudes [15,16]. Scholars moreover address these in ways that move beyond a Global South — Global North binary, instead focusing on socio-spatial and political-economic patterns and drivers [17–22]. Thus, scholarship reflects that decisions on solar PV roll-out embody socio-spatial and political-economic complexity. This includes a trans-local focus on the supply chains [23] and 'afterlives' [24] of solar PV modules, and on the varied actors [25] and evolving standards [26] that drive PV roll-out, including actors at the global scale such as energy agencies [27] who enable transnational cross-fertilisation and coordination.
- (ii) Advances in roll-out at utility scale creates some clear cross-sectoral risks in sectors like land and finance, such as large rural land footprints for urban supply [28,29], the need for large investments in electricity transmission infrastructure [30–33], and exclusion of smaller investors from solar roll-out [34–37]. Research on these issues has identified scope to address these risks as opportunities for innovation and policy adjustment [28,30,38,31,37]. Yet, studies show that energy sector governance is heavily structured by political-economic factors such as

institutional path-dependencies and powerful incumbents [8,39–41], where large entrenched actors exert undue influence on policymakers to serve their own interests, both as fossil fuel incumbents who slow down solar roll-out and as large solar developers who seek to dominate the sector. These tendencies in decision-making can severely undermine solar PV roll-out at the local scale [5,18,19,26,35], and reduce the contribution of PV plants to climate mitigation by necessitating investments in carbon intensive electricity transmission grids [22,37,42].

- (iii) Progress on community energy and small-scale PV plants has been slower than at utility scale. This is cause for concern, as research shows clearly that the former can be beneficial for energy justice [20,34,43–45], and advance equity and universal clean energy access goals. Nonetheless, notable emerging trends include community solar PV projects [5,43,46], electric vehicles and energy storage technologies [2,45], energy flexibility solutions [42,48], and off-grid and micro-grid plants [25,49,50]. Decision-makers can draw on insights regarding diffusion pathways for small PV plants, such as neighbourhood influence [51], post-adoption user behaviour [52], the effects of subsidies [53], price signalling [36] and hybrid business models [18] on adoption patterns, and interaction effects with other technologies embedded in energy practices [9,39]. There is an urgent need to use lessons from small-scale solar PV plants for future rapid growth of emerging complementary technologies such as energy storage and batteries that enable energy flexibility [2,42,48].

Overall, decision-making on solar PV roll-out displays characteristics of what we can term 'scalar bias' — meaning that legal-regulatory and political-economic structural conditions favour utility scale roll-out over roll-out at local and community scales. Research cited above concurs in attributing this to political-economic factors such as incumbency and institutional path-dependencies, as well as legislative and bureaucratic rigidity and sectoral silos. For instance, the Portuguese solar PV roll-out only took off when structural changes by the executive agency enabled large-scale PV auctions. By contrast, the country's small-scale PV roll-out required legislative changes whose implementation has been slower, with persistent structural and financial barriers [26]. A wide range of experiences with small-scale solar PV diffusion reveal similar patterns of lack of adequately coordinated central support and financing [33,35,44], whereas large-scale solar PV roll-outs have benefitted from such support [37,40,54]. While precise definitions vary by country, large PV plants are in megawatts — and recently gigawatts — while small PV plant capacities range from a few solar panels to hundreds of kilowatts.

It is apparent that rapid changes are underway. Decision-making is increasingly being recognised as context-specific both at multiple scales and at multiple levels of governance, as well as in terms of socio-spatial patterns in PV plant installation. Yet the pace of change varies across scale, and it appears that actors in large-scale solar PV roll-out are able to exert greater influence and access more opportunities than actors in small-scale PV projects. This reflects poorly on sectoral decision-making, which must anticipate such a challenge and draw more proactively on insights to rectify scalar biases.

Theoretical review: the political economy and scalar biases of solar PV roll-out governance

To understand the broader effects of this ‘scalar bias’ in decision-making in solar PV roll-out, we next assess insights in the literature concerning substantial outcomes for rapid and deep decarbonisation and energy justice. Given that extant scholarship suggests that structural (legal-regulatory and political-economic) conditions allow large-scale solar to proceed much faster than community-based solar PV plants (due to incumbency politics and differential bureaucratic barriers), it is important to assess existing knowledge on decision-making processes that can ensure rapid solar roll-out with sustainable cross-sectoral and distributive justice effects. Reviewing this literature, we identify two clear research lacunae:

- (i) It is clear that factors such as livelihoods, stranded assets (of energy companies deeply invested in fossil fuel reserves that may be rendered uncompetitive) and political stakes [2], and contextually specific dynamics [3] hold the key to determine the substantive outcomes of PV roll-out trajectories. Nevertheless, much of the focus in solar energy transition studies is on evaluating prospects and outcomes in terms of installed capacity, solar potential and spatial distribution. Technical and economic assessments would do well to integrate more granular understandings of political-economic feasibility to provide actionable analytical inputs to decision-makers. Limited but growing attention to socio-political pathways [6–9] highlights the importance of explicitly tackling politics of incumbency, providing a reliable policy horizon to facilitate the entry of new actors at multiple scales, and enabling the institutionalisation of solar PV in wider sectoral logics. These socio-political dynamics have justice effects [10,22,37] that merit attention.
- (ii) The state-of-the-art literature on decision-making in solar roll-out remains divided along the lines of established epistemic communities. Whereas a primary focus on such decision-making still remains conspicuously absent in some leading technical journals (*The Electricity Journal*, *Environmental Research Letters*), other technically oriented journals (*Applied*

Energy, *Renewable Energy*) feature such an emerging focus. Notably, journals featuring energy social science (*Energy Research & Social Science* (established 2014), *Environmental Innovation and Societal Transitions* (established 2011)) have gained prominence, underpinned the growth of coherent epistemic communities, and offer richly contextualised accounts of institutional and relational aspects of energy governance. Moreover, there is incipient attention to this issue in development and human geography journals (*World Development*, *Geoforum*, *Environment and Planning C: Politics and Space*, *Antipode*), which foreground established ways of addressing transition *politics* and power dynamics as the mainframe. Despite wide-ranging recognition across these platforms that scalar biases characterise solar PV roll-out, few contributions have thus far addressed this issue explicitly in terms of its implications for decision-making.

Thus, we identify a need for political-economic framings to drive studies on decision-making in solar PV roll-out, and in particular, for such studies to systematically address scalar biases that risk excluding small-scale actors and distributing solar PV benefits and burdens unjustly. Some reviewed papers offer key insights on political

Table 1

Emerging insights to address political-economic and scalar drivers in solar PV roll-out

[7]**	Identifies a range of solar prosumer pathways highlighting the role of market and regulatory provisions based on comparing trajectories in Germany, Norway and the UK.
[2]**	Emphasises the importance of national policy in enabling massive rapid PV roll-out, arguing that targeted trajectories demand attention to cross-sectoral political effects.
[40]**	Maps changes in discursive framings of solar PV driven by incumbents, with portrayals evolving from threats into opportunities, as industrial actors realigned their positions.
[24]**	Directs attention to life-cycle aspects of solar PV roll-out across geographies and draws on a study in Kenya to present perspectives embedded in cultures and economies of repair.
[21]**	Emphasises the material politics of the global solar energy sector and uses the cases of India to show the limits of national political economy in enabling a just energy transition.
[17]*	Specifies how policy-implementation gaps relate to flexibility in solar roll-out and actors’ agency and ability to improvise, based on comparing local access projects in six countries.
[3]*	Argues for the importance of situating decision-making within contextual needs and complementing technological transitions with place-based adaptation, based on a review.
[46]*	Maps the complex entanglements of enabling community solar PV plants under legislative restrictions and brings to the fore the social and landscape level justice issues at stake.
[29]*	Provides a rare example of a mixed methods study that addresses cross-sectoral impacts of multi-scalar solar PV roll-out with sensitivity to both technology and policy constraints.
[47]*	Combines a focus on the emergence of solar PV and electric vehicle charging to argue that large incumbents capitalise on their position and shape early trajectories to their benefit.

economy (**) and scalar biases (*) that we highlight as useful points of departure in Table 1.

Conclusion: the need to build strong, enduring political constituencies

To conclude, we suggest how future research can build on identified lacunae, and we offer reflections to improve decision-making during solar PV roll-out by addressing potential unjust effects of scalar bias, such as exclusion of small-scale actors (a failure of recognition and procedural justice) as well as unjust distributive outcomes.

An encouraging finding in our review is that a diverse set of country case studies [10–12,14,19,25,26,30,33,41,54] offer a firm and broad basis to inform political-economic approaches to decision-making in their own and similar solar PV roll-outs. These analyses of governance in diverse energy geographies offer insights into a variety of approaches to address scalar biases and unjust outcomes of solar PV roll-out. Policy-oriented research could use these as a foundation to reconfigure policy priorities and inform action for more inclusive and evenly distributive roll-outs at multiple scales.

A more worrying aspect is whether recommendations on how actors can steer rapid, multi-scalar solar PV roll-out will find an audience among decision-makers. The reason is precisely the political-economic factors identified by the above studies: incumbency tactics, institutional path-dependencies and power differentials in actors' agency. We see scope for cautious optimism here due to the rapid cost declines that make solar PV a globally economically competitive energy source [1: p.12]. Combined with political backing through clean energy policies whose ambition is increasing (e.g. the European Commission's target of 55 percent emission reduction by 2030), solar PV is now undeniably attractive to most national governments, and increasingly to local governments through innovative community energy models.

In fact, we argue that adequate appreciation of scale and justice effects in decision-making can ensure that governance decisions to implement solar PV roll-out get ahead of the curve and gather strong, enduring political constituencies, with political-economic payoffs. As already evident in some cited studies, these payoffs extend beyond solar technologies and climate mitigation decisions, to key ballot-box issues such as land, agriculture and transmission infrastructure. When configured rightly, project siting, electrification, benefit-sharing and burden-sharing, and improved clean energy access can create strong public support among diverse constituencies, and shape enduring coalitions based on a common notion of energy citizenship. Responsive governance will allow governments to capitalise on support from wide-ranging constituents cutting across party lines, and in turn open up regulatory space to address more technocratic aspects that

remain marginal in public discourse but are nonetheless crucial to enable rapid, deep and just decarbonisation through solar PV roll-out. These include trans-local material impacts of solar PV (e.g. targeted through procurement rules that promote circular economy), and structural barriers to access and participation (e.g. mitigated through community energy legislation), which require multi-level decisions suited to contextual specificities.

In sum, even as attention to drivers of decision-making in solar PV roll-out is key to climate mitigation, research on its political-economic nature and scalar biases must be translated into policy forums. Academic platforms reflect a move in this direction, but must hybridise even more, so that governance solutions direct the nature of enquiry on this socio-technical transition. Timing and representation of a diversity of needs is critical to address scalar injustice through legislative resolve and public backing for a just energy transition. Hearteningly, our review identifies knowledge on requisite policy adjustments.

Conflict of interest statement

Nothing declared.

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