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Desert geographies: solar energy governance for just transitions

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ABSTRACT

While sustainability statements crowd national and urban visions, unjust implementation of lower-carbon energy infrastructures for climate mitigation manifests in contexts of marginal rurality. We focus on solar energy infrastructure rollout in Rajasthan in Western India to argue for a response centred on the energy practices of, and the effects of energy development on, politically marginal inhabitants. To that end, we consider what environmental governance arrangements under transition reveal about the recursive relationship between socio-material reconfiguration of the energy sector and co-evolving power relations and institutional structures. We propose and operationalize three concepts that can guide contextualized analyses of institutional, relational and socio-material change. These bridging concepts identify and inform pathways for just, publicly accountable transitions. We argue that environmental governance and energy geographies insights can orientate just transitions away from renewed extraction and growth-wedded economic paradigms prevalent in post-colonial geopolitics, and towards using appropriate technologies to attain decent living services.

KEYWORDS

Environmental governance; political ecology; energy geographies; solar transitions; India; power

Introduction

In a modality comprising globalization and growth-oriented neoliberal capitalism, academic debates on energy transitions must be mindful of their relevance at a tautly contested historical conjuncture. On the one hand, energy systems are battling over a deep rift between incumbents and proponents of lower-carbon energy infrastructures,[1] as large low-carbon transitions gather pace, while fossil fuel contractions remain slow or oppositely oriented (Smil, 2017). On the other hand, the acceleration of lower-carbon energy rollout continues the supply-side domination of energy sector governance. This entails ownership by large financial actors, decision-making at high levels away from citizen interests and agency, and infrastructural arrangements suited to maintaining centralized control. While sustainability statements crowd national and urban visions, the neglect of actual user needs manifests in persistent social imaginaries of marginal rurality.

Amidst these transformations, academics largely inhabit urban contexts, with limited time and ability to study remote places on the margins of energy transitions. Recent pandemic circumstances exacerbate this limitation. What actionable knowledge can research generate to advance causes of marginalized communities deeply impacted by interventions that cater to the desires of the current

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modality and a growth-oriented global economy that inflicts structural and *slow* violence?[2] Within voluminous recent energy transitions research, ethnographic work on energy justice, social fragmentation, and ecological degradation caused by lower-carbon energy infrastructures in rural hinterlands remain marginal (though see for example Dunlap & Correa Arce, 2021; Franquesa, 2018; Yenneti et al., 2016). Historic and socio-cultural implications of colonial legacies extend into debates on energy, e.g. in India from Nehru's[3] vision of national transformation through electricity to electricity sector reforms with neoliberal reorientation through the Electricity Act of 2003, clearing space for private firms and global markets (Kale, 2014). Faced with this political economy of a sector in transition, what is needed for a responsible academic response, given that scientific knowledge is not independent of its political economic context and the politics of knowledge often reinforce hegemonic relations in energy (Stock, 2021) and sustainability transitions more broadly (Arora, 2019)?

We conceptualize three core bridging concepts to approach these questions in a study of solar development in the desert reaches of Rajasthan in Western India, to argue for a response centred on the energy practices of politically marginal residents in co-dependent relation with nature. Customary dependence on biomass and charcoal can be substituted by increasingly affordable alternatives such as solar cookers, solar energy and micro-grids, and access to expanding electric grids with lower-carbon energy mixes to meet the needs of subsistence agricultural households. Shifts in sectoral transitions from coal to lower-carbon sources can be accompanied by revenue-sharing arrangements and reversals in trends of land-use change without direct involvement and benefit sharing with local populations. Such measures can work to prevent land grabbing or green grabbing practices that alienate marginalized peoples from land, by restructuring authority over natural resources, labour relations, and the relationship between human and more-than-human worlds (Stock & Birkenholtz, 2021). Recent decades have exposed the limitations and failures of progressive state action in reversing anthropogenic climate change, revealing the imperative of voluntary action, mutual aid, and direct action (Sovacool & Dunlap, 2022) in response to the climate crisis (Clark, 2020). We therefore propose energy geography insights guided by three overlapping bridging concepts of *institutional change*, *accountability change*, and *socio-material change*, to inform a pathway for transitions in publicly accountable ways.

Local and global tools to meet the challenge of energy transformation

Recent climate events, such as droughts and wildfires, are a wake-up call about the climate challenge. Climate science has established that an appropriate response to a changing climate entails rapid, drastic reduction of greenhouse gas – notably including carbon – emissions (IPCC, 2018). To aid low-carbon transitions, social scientists must critique political-economic resistance to shifts away from carbon-emitting activities while identifying strategies for democratic and socio-ecologically just reduction in energy throughput and transitions to lower-carbon energy in line with broader public interests. It is important to secure these interests in just ways such as community ownership, while critically evaluating whom energy services benefit, mindful of dominant logics of energy commodification (Stirling, 2014). Until recently, engineering and economic analyses dominated energy studies. This has changed, with burgeoning scholarship on socio-political aspects key to mobilize shifts towards inclusive, equitable and clean energy futures (van Veelen et al., 2019). Yet social science scholarship on systemic energy transformation remains poorly funded (Overland & Sovacool, 2020). Strands of growing literature on transitions must converge for interdisciplinary insights to inform policy and practice (Markard et al., 2012).

Within lower-carbon energy infrastructure rollout for climate mitigation, solar energy uptake merits particular attention. By 2020, installed solar capacity had reached 580 Giga Watt (GW) – nearly 23% – of 2537 GW of installed lower-carbon energy capacity globally (IRENA, 2020); and solar constituted 97 GW or 55% of the 176 GW of new lower-carbon energy capacity installed globally during 2019. To analyse this transition, we operationalize the tripartite framework of structural, relational and material change that Sareen and Haarstad (2018) proposed to wed socio-technical and justice aspects of energy transitions – represented here as institutional change (related to structural aspects), accountability change (related to relational aspects), and material change (related to infrastructural aspects) respectively. Whereas the original framework draws on multi-scalar empirical cases of solar uptake in Portugal, we consider its implications for an upcoming study of solar rollout in the rural desert reaches of Rajasthan.

The Thar desert is home to one of the most ambitious solar rollouts globally, and one of India's poorest regions. Despite a large and diverse economy, India's large population of nearly 1.4 billion struggles to meet basic needs (Rao et al., 2019) due to rampant income inequality; the top decile holds over three-fourths of wealth. These poverty and inequality trends are apparent in India's unequal distribution of energy access and energy poverty, with per capita electricity consumption well below the global average. Despite the development of solar parks having led to more precarity and energy insecurity for communities affected by the megaprojects (Stock & Birkenholtz, 2021), India's 175 GW lower-carbon energy installation target – including 100 GW of solar power by 2022 – discursively legitimates their rollout with goals such as meeting global climate mitigation commitments, facilitating employment, and 'safeguarding [the] interests of the end consumer' (Government of Rajasthan, 2019, p. 9).

Rajasthan's Bhadla solar farm, which consists of three phases operated by six companies over one massive swathe of land, is expected to add over 2.2 GW of energy capacity (Paliwal & Dave, 2021). This largest solar farm worldwide is under implementation even as medium- and small-scale projects struggle with a competitive disadvantage in securing land concessions and single-window clearances for solar licenses, setting back potentially better environmental justice outcomes (Sareen & Kale, 2018). Industrial-scale projects often usurp commons by discursively transforming them into 'wastelands' – using a classification created by the British Raj to perpetuate neocolonial relations of production (Baka, 2017; Stock, 2021) – thus creating spaces to attract domestic and foreign private investments. The sacrifices brought about by megaprojects in Rajasthan and elsewhere in India depriving some communities of livelihoods and their customary lifestyles are justified by positive promises of development for the 'greater good' that sometimes accompany implementation by extra-legal means (Levien, 2012; Yenneti et al., 2016).

A response to climate change demands the cessation of extracting fossil fuels (Jakob & Hilaire, 2015) while implanting lower-carbon energy to the extent necessitated for providing decent living conditions. Solar technologies can enable energy-poor rural households to own the means of energy production and co-define terms of access that safeguard against co-optation by powerful, entrenched actors, aligned with principles of energy democracy (Burke & Stephens, 2018; Szulecki, 2018). Research argues that decentralized energy systems are essential for inclusive access to cleaner energy (Alstone et al., 2015). Yet, analyses of engineering and economic barriers have struggled to capture how institutional contexts can make or break systems, and neglected developments outside their narrowly-defined foci (Harriss-White et al., 2009). Institutional analyses often feature political science perspectives, with large-scale statistical studies on national-level institutional forms (e.g. Brew-Hammond, 2010). These modalities often reproduce social inequalities as they implement solar photovoltaic infrastructures (Stock, 2021). By contrast, we draw from scholarship that

addresses the characteristics of emergent local energy systems under transition vis-à-vis the interplay of national institutional contexts and established regional energy utilities (cf. Kale, 2014; Mahoney & Thelen, 2010). Our contribution is part of a collective push towards transformative methods for research and practice based on overcoming 'anachronistic pedagogy, mismatched incentives, insufficient expertise, lack of personal commitment, and insular products and communication' (van der Leeuw et al., 2012, p. 115). To foreground environmental governance concepts in systemic energy transformation research, we focus on material and institutional changes and on multi-level accountability in reconfiguration.

Contemporary energy sectors constitute a frontier with competing interests at stake as new energy sources seek to territorialize a system where fossil fuel incumbents actively resist their own deterritorialisation; a tendency that shapes development in Eurasian contexts given fossil fuel legacies. We propose tracing such reconfiguration in terms of institutions, accountability and socio-materiality. We operationalize these bridging concepts as part of a boundary crossing language (Clark et al., 2017) between different emerging traditions of scholarship on the governance of solar energy uptake. We aim to show that the bridging concepts of institutional change, accountability changes, and socio-material change offer a means for empirically engaged study in contexts such as Rajasthan.

In what follows, we first characterize scholarship on solar uptake to show the need for bridging concepts. Then, we relate these concepts to energy geographies research and interdisciplinarity. Thereafter, we operationalize the concepts with a theoretical underpinning in environmental governance scholarship, and indicate paths forward for structured engagement in Rajasthan. The concluding section argues for situated application of bridging concepts to enable integrated, empirically-informed analyses of energy transformation.

Why we need bridging concepts: research on solar energy uptake

The case of solar uptake research demonstrates the need for bridging concepts to synthesize disparate debates on energy transitions. Synthesis can mobilize sustainable action based on a holistic understanding of changes in energy sectors and their wider context. Mapping a trajectory for decentralized solar energy systems, both off-grid and with grid integration, is a challenge for such research. Distributed growth can play a role to enable local energy consumption and grid substitution. Well-coordinated grid integration can enable solar prosuming to displace carbon-emitting sources and complement other low-carbon sources. In a landscape of shifting actors, institutional change must accompany infrastructural change. This impacts decision-making structures and the allocation of costs and benefits. As a potentially disruptive technology, solar energy implementation must address problems of political will and lock-in advantages of carbon-based energy supply, which involves changes in policies, institutions and energy solutions. As Stirling (2019, p. 1) observes, 'even where these neglected alternative pathways are scientifically realistic, technically practicable, environmentally feasible and socially viable, dynamics of incumbency can prevent them becoming historically realisable'. Overcoming these trends requires strong environmental governance institutions, which have the capacity to implement change, can withstand countervailing forces, and have strong accountability embedded in them (Dubash, 2021).

A growing literature emphasizes the promise of solar energy uptake for relatively energy-poor but geographically well-located countries.[4] Research and mainstream media coverage show rapid technical progress and increasing affordability: solar growth and affordability are already in place (IEA, 2017). But research also highlights the challenges of inclusion and local capacity-

building (Wambuguh, 2013), regulation and accountability in rural energy supply (Martinot & Reiche, 2000), and of institutional roadblocks and intransigent policies (Yadoo & Cruickshank, 2012) for widespread solar energy use. Thus, to understand the governance of solar energy transitions, we require concepts that enable combined and contextualized analyses of institutional, relational and socio-material change.

A review of solar governance research during 2018–2020 notes that scholars (i) increasingly analyse multi-scalar dynamics of transition, (ii) identify cross-sectoral risks of utility-scale solar in land and finance sectors, and (iii) find concerns of exclusion and slow progress in community and small-scale solar rollout (Sareen & Haarstad, 2021). Sareen and Haarstad (2021, p. 25) therefore argue that solar energy governance suffers from a 'scalar bias' where 'legal-regulatory and political-economic structural conditions favour utility scale roll-out over roll-out at local and community scales'. Indeed, country-specific studies show that solar rollout dynamics are historically and geographically shaped (Kirshner et al., 2019); feature significant sub-national differences with attendant equity implications (Zhang et al., 2020); are deeply affected by the political economy of related sectors like land (Stock & Birkenholtz, 2021); and risk engendering conflicts and exacerbating inequalities unless appropriately situated within local contexts (Roddis et al., 2020). Thus, scholars highlight a need to examine changes in institutions, accountability and materiality using diverse terms and theories. This requires interdisciplinary engagement to address key real-world challenges such as enabling solar uptake for just energy transitions (Clark et al., 2017; Pellegrino & Musy, 2017).

Such ambitions have nuanced and unique challenges given the colonial past and postcolonial dimensions of life and society in India. When Nehru took the helm of an independent India, with a total electricity capacity of 1.7 GW, only a small fraction had access to electricity. Nehru hoped modernization through the expansion of electricity and its implications would lead to a unified India. Over 70 years later, despite four decades of planned economic development, energy consumption per capita remains well below the global average. The electricity act of 1948 left it largely to the states to decide how to plan their electrification programme, thus the extent to which rural electrification is prioritized depends on the extent to which agrarian interests determine developmental agendas (Kale, 2014).

Beginning with Truman's inauguration speech in 1949, when he infamously argued that half of the world came from 'underdeveloped areas', a new era began with the certainty of Victorian rectitude that advanced societies had a moral obligation to assist and civilize so-called backward nations (Davis, 2009). This endeavour played well to the interests of colonizing nations, through a net appropriation of labour and resources from formerly colonized nations (Dorninger et al., 2021). As pointed out by Davis (2009, p. 113), 'development for the vast majority of the people of the world has been a process in which the individual is torn from his past, propelled into an uncertain future, only to secure a place on the bottom rung of an economic ladder that goes nowhere'. In the context of post-colonial India, Chabot and Vinthagen (2015) observe that scholars often idealize Gandhi for his work on *satyagraha* or non-violence in pursuit of truth, but routinely ignore his dedication to decolonization. Gandhi opposed not just the colonial state, but also the colonizing impact of modern civilization. Fearing that the removal of the British without institutional transformation would have distressing consequences for the poor, he pursued decolonization that went beyond politics to cultural and spiritual *swaraj* or self-rule (Chabot & Vinthagen, 2015). Mindful of this distinctive socio-political history, the next section presents the three bridging concepts, which we then operationalize for Rajasthan, with a theoretical underpinning in environmental governance scholarship.

Bridging concepts for energy transition analysis

From the social meaning of electric infrastructure a century ago in the USA (Nye, 1992) to the regional political economies of current electrification in India (Kale, 2014), the social sciences have come to recognize that energy sources and infrastructures are deeply intertwined with socio-political forms of organization (Mitchell, 2011). Specifically, energy geographers demand attentiveness to 'location, landscape, territoriality, spatial differentiation, scaling, and spatial embeddedness' (Bridge et al., 2013, p. 331), and anthropologists highlight the recursive agency of links between energy and culture (Boyer, 2015). Calls to attend to politics and power within transition management scholarship also underscore the importance of socio-ecological and institutional perspectives for enabling sustainability transformations (Loorbach et al., 2017).

In this midst, as pointed out by Stirling (2019, pp. 2–3) it is important to recognize the limitations of performing 'vertical policy interventions choreographed from a notional governance "cock-pit,"' and acknowledge the importance of 'horizontal and mutualistic forms of political action'. This effort requires not just institutional change, but also an empathic modality that allows for the flourishing of 'many less visible movements and peoples throughout the world [who] are also engaged in resurgence as they reconnect to reach or to recover sufficiency and remake territories and worlds threatened by growth-driven development, neoliberal globalization, and climate change' (Nirmal & Rocheleau, 2019, p. 478).

Discussions of energy transitions often take place amongst those with similar entry points rather than between those with diverse understandings (Luederitz et al., 2017). To bridge such discussions, this section presents three bridging concepts and shows how they can integrate energy geographies concerns (Bridge et al., 2013) related to key aspects of solar uptake, notably grid integration and distributed growth:

(1) Bridging Concept 1 (institutional change) can help underscore the role of socio-political dynamics in driving sectoral change in a particular context (*location*) and across contexts both in terms of size and space (*spatial differentiation* and *scaling*). This concerns the implications of new actors and institutions emerging as old ones adapt to changing energy sector logics. Such changes reconfigure stakes for incumbents,[5] and problematize the politics of knowledge and expertise in energy governance as heads of industries and utilities segue into roles of regulators, association representatives, energy consultants and advocates.
(2) Bridging Concept 2 (accountability changes) can examine why particular enablements or constraints are put in play by tracing changing accountability relations in a given context (*spatial embeddedness*). This concerns the role of diverse parties ranging from the citizenry to high-level decision-makers in keeping energy governance responsive to environmental and socio-economic interests for a just energy transition.
(3) Bridging Concept 3 (socio-material change) can guide interpretations of how infrastructural change affects a multiplicity of peoples and actors, as well as, where such changes could be made to what end (*location and landscape*). This concerns the agency of infrastructure, the inertia of entrenched technologies and enablements of emerging energy infrastructures as policymakers, regulators, investors and users alongside movements engage in rapid, uncertain sociotechnical innovation.

Thus, one can capture the whole gamut of issues pertaining to solar uptake that energy geographies encompass: altering the generation mix; ensuring grid capacity in new locations or creating

alternatives; changing regulations to develop various market and non-market settings for new energy production configurations across time and space; creating mechanisms for participation in decisions that affect common energy futures; optimizing distributed generation in terms of space and scale by leveraging emerging techno-economic advances; transitioning to new forms of ownership; ensuring stability by establishing standards in dialogue with experts while avoiding conflicts of interest; and democratically reducing energy and material throughput, to name a few.

In solar energy rollout in Rajasthan, for instance, there has been a diverse array of old and new actors weighing in with a multiplicity of tactics. This includes small-scale actors such as Frontier Markets who target distributed solar product diffusion in rural areas, targeting better socio-economic outcomes for women; innovative efforts carried out by the Barefoot College for community-scale rural electrification through '"effective" and "transformative" changes that are directly intertwined with the energy technology programme' called *solar mama* (Mininni, 2022, p. 120); and mega-scale projects – such as the Bhadla Solar Park with a capacity of 2245 MW spread over 5700 hectares of land in Jodhpur district – that are deeply steeped in the modalities of our times, and attract large-scale investments from entrenched and new actors alike. Changes in accountability pertain to criticisms of schemes to promote solar energy, which in their current form have led to advocates of small and medium-scale solar energy implementation being outcompeted due to structural disadvantages created by policy instruments orientated towards large players. The nature of socio-material change is evident in the form of energy infrastructure implemented, not just in scale, but also in its source, more specifically the expansion of solar energy alongside coal power, and the forms of ownership and interaction they enable.

Several things are at stake in such a context, especially amongst marginalized rural residents, as is true of much of the larger Eurasian region with its political complexities, top-down energy sector legacies and sprawling populations and energy geographies. Some chief stakes consist of lack of participation, socio-material incumbency, and imposed competitive disdvantage on small- and medium-scale players. Sareen and Kale (2018, p. 276) note that local peoples' involvement has in practice been marginal, while electricity distribution companies and fossil-based corporations use their lobby power to resist sectoral changes that would unlock just (e.g. decentralization), sustainable (e.g. small-scale subsistence-oriented technologies) outcomes. While policy instruments have encouraged lower-carbon energy infrastructure expansion for universal electricity access and decarbonization, large players have used superior access to capital to corner benefits. Citing Mbembe, Larkin (2013, p. 334) reflects that 'often the function of awarding infrastructural projects has far more to do with gaining access to government contracts and rewarding patron-client networks than it has to do with their technical function'. Sareen and Kale (2018, p. 275) quote an industry representative in Western India in similar vein: 'everyone knows these things work on a commission basis, that is why the government is only favouring large players'.

In recognition of the need for boundary-spanning in interdisciplinary studies of socio-technical change, transitions scholars call for defining governance problems, establishing shared concepts, and developing bridging metrics (Turnheim et al., 2015). Converging energy governance research for just transitions requires advancing 'forms of *inter*disciplinary autonomy and rigorous interdisciplinarity that lead to the production of new objects and practices of knowledge' (Barry et al., 2008, p. 42). Integrative efforts within the scientific community call for a 'safe operating space' (Pereira et al., 2015, p. 6027), which would help draw energy geographies insights into socio-technical literature, to unpack the formation of institutional authority over resource use (Sikor & Lund, 2009) and situate political processes within changing contexts.

We now operationalize the bridging concepts as questions for an upcoming study of solar energy rollout in Rajasthan and specify theoretical underpinning in environmental governance research. Interpreting environmental governance arrangements under transition can articulate how power relations and institutional structures co-evolve with socio-material reconfiguration (Huber, 2013). This operationalization is informed by scholarship on the social construction of technological systems (Bijker et al., 2012), on the evolution of particular authoritative institutional forms (Nightingale & Ojha, 2013; Sikor & Lund, 2009), and on institutional change and implementation politics (Cleaver, 2002; Manor, 2011).

Operationalizing three bridging concepts to analyse solar rollout

The bridging concepts regard institutions as socially embedded outcomes of political and material struggles (Cleaver, 2002), that structure negotiations between interests that compete to legitimate their power and thereby gain authority to reconfigure access to resources (Nightingale & Ojha, 2013). For solar uptake, resources comprise energy infrastructure and flows. Taking instruction from the ethnography of infrastructure (Star, 1999/2016), we specify the use of these concepts to study how actors socially construct technologies (Bijker et al., 2012). We highlight pertinent operationalisations from scholarship on energy geographies and environmental governance for each corresponding question.

Bridging concept 1 (institutional change) operationalized for solar uptake: as both private and public providers begin to offer solar power and solar power systems, how does institutional change reconfigure authority under transition?

This question requires a multi-level institutional analysis of (i) the repercussions of *global* energy politics, (ii) *national* sectoral policies, (iii) *regional* operationalization through institutions and infrastructure, and (iv) *local* implementation through rural energy suppliers. As the solar sector shifts towards privatized, localized energy delivery, this concept focuses on the factors shaping authority. It builds on institutional bricolage by attending to 'institutions, the politico-economic context and discourses across governance and government levels' (Clement, 2009, p. 129) to situate institutional changes in specific contexts.

Institutional authority in the energy sector typically concerns top-down recognition through governmental regulation. Yet energy suppliers assume authority by procuring licensed equipment through global supply chains and through acknowledgement by payments from users. The concept of 'authoritative institutional forms' shows how 'antecedent forms of authority' are challenged or reinforced (Nightingale & Ojha, 2013, p. 29) during energy transitions, bringing work on the recursive relationship between the act of authorization and the formation of institutional authority (Sikor & Lund, 2009) to bear on the energy sector. This conceptualization analyses mutual recognition between energy regulators, suppliers and users.

Along these lines, Koch and Perreault (2018) show that resource allocation decisions are politically shaped by multi-scalar tussles over identity that produce institutional authority. Curley (2018) shows how energy transitions serve to impose changes in institutional logics – e.g. from public towards private investment, and from customary authority to standardized local government. Eadson and Foden (2019) show that energy markets are socio-political constructions that favour particular actors, problematizing ideas of actors as inside or outside energy markets. Bridge et al. (2020) argue that institutions such as carbon markets construe risk in a manner that legitimates

certain forms of energy over others, with material consequences for the nature of sectoral change. These contributions within energy geographies highlight the recursive relationship between energy transitions and socio-political authority.

India's energy sector is affected by an amalgam of federal and state policies, a form of *energy federalism* (Sareen & Kale, 2018). Initiatives such as the *International Solar Association* and *One Sun One World One Grid* where India has taken leading roles seek to frame global energy cooperation and impact domestic energy politics. They entail obligations such as reducing the emission intensity of India's economy and increasing lower-carbon sources in its energy mix in time-bound ways. In Rajasthan, emulating the Bhadla project, even larger solar projects such as the Sambhar Ultra-Mega Project (4 GW requiring over 9000 hectares) are emerging (Paliwal & Dave, 2021). These multi-spatial developments necessitate institutional changes whose implications for the lived experience of inhabitants merit scholarly attention.

Bridging concept 2 (accountability change) operationalized for solar uptake: what accountability relations are in place between energy suppliers and poor households, and how do they impact low-emissions sectoral development?

This question investigates how changing sectoral accountability relations impact sustainability and inclusion: e.g. some companies target poor off-grid households with solar devices that have low up-front costs, must be paid off through weekly instalments using mobile banking, and can be remotely deactivated if loan recovery fails. Other companies provide urban solar energy systems with no downpayment, using power purchase agreements with multi-year energy tariffs for solar generation on clients' rooftops. Policies to ensure accountability must ensure grievance redressal mechanisms, affordable long-run energy rates, and safeguards against exclusion or heavy indebtedness. Solar adoption targets require measures that establish such reference points for accountability. Notably, Sustainable Development Goal 7 does little to address socio-political elements of provisioning universal clean energy, which can give rise to newly vulnerable groups (Menton et al., 2020), e.g. through land grabbing.

Political ecology offers insights into vertical and horizontal accountability relations (Manor, 2011), and puts forward methods to trace and analyse accountability relations using material artefacts (Kraft & Wolf, 2018) and both formal and informal practices of legitimation (Sareen, 2019). Artefacts provide the appearance of accountability by enacting legitimation (e.g. environmental impact assessment reports), but such legitimation must be substantive (e.g. sanctions on projects that violate environmental laws) and comprehensive (e.g. cognisant of political lobbying that disadvantages some actors). Emerging relations can be examined in terms of their potential for 'deep upscaling' (reaching the poorest) and 'institutional upscaling' (realizing requisite change) (Jolly et al., 2012, p. 199). How these relations change or persist can be understood by juxtaposing 'neglect and nurture' (Oskarsson & Nielsen, 2014, p. 267) at multiple levels.

In an influential energy geographies work, Lawhon and Murphy (2012) characterize decision-making in socio-technical transitions as power-ridden, raising questions of public accountability. Shirani et al. (2017) explicate how intersecting factors determine the ability to influence energy transitions, including temporality, social identity and relationships. Kirshner et al. (2019) show that solar adoption involves situated place-making and changing social relations. Haarstad and Wanvik (2016) adopt a similar relational stance, approaching energy transitions as dynamic shifts in how assembled systems territorialize space. As Scott (1998) notes, states use infrastructure as a

major vector to organize society. Thus, scholars recognize energy transitions as relational power struggles over accountability in changing fields of situated actors.

In Rajasthan, shifting accountability relations are evident in the emergence of new actors and adjustment and resistance by incumbents in a rapidly changing energy landscape. By 2017, solar power became competitive over coal power, sparking cancellations of tens of GW of coal plants. This diverted energy actors to Bhadla, where financial incumbents navigated evolving regulatory frameworks through new and reconfigured market actors. However, as Sareen and Kale (2018, p. 276) highlighted, no sectoral actors 'conveyed a sense of conviction that ordinary people could get seriously involved in determining the energy sector trajectory'. This reflects a missed opportunity for citizen ownership in energy transitions, undergirded by fragmented accountability relations that allowed the reproduction of power relations.

Bridging concept 3 (socio-material change) operationalized for solar uptake: how does the socio-materiality of distributed solar energy solutions alter an energy sector historically dominated by fossil fuel based supply?

In remote areas where grid extension is costly, distributed solar energy solutions can reach poor households by generating power locally, whereas urban users in densely populated areas often face space constraints for in-situ solar generation. Regulations rarely allow simple profitable prosumption, making solar adopters reliant on a combination of smart meters, aggregation and storage technologies, and evolving energy flexibility markets. This question addresses how solar solutions expand choices for users dependent on large-scale utilities, kerosene or low-grade coal, accompanied by new infrastructure, payment options, and diverse devices such as solar cookers, solar panels with battery storage, and concentrating solar power facilities with flexible and firm energy delivery (Trieb et al., 2014).

This question can be probed using the notion of a 'market device', or 'the material and discursive assemblages that intervene in the construction of markets' (Muniesa et al., 2007, p. 2). Studying these assemblages reveals how technological systems are socially constructed (Bijker et al., 2012) by focusing on materiality, as Cross (2013) shows for affordable solar lamps. Such approaches posit that 'the shape and meanings of a technology […] are acquired through the heterogeneity of social interactions' (Bawakyillenuo, 2012, p. 410). The latter can be understood through an 'institutional bricolage' approach, which sees institutions as 'embedded in everyday relations, networks of reciprocity and the negotiation of cultural norms' by borrowing from 'sanctioned social relationships' (Cleaver, 2002, pp. 15–16). This conceptualization focuses on recursive interactions between technologies and sociopolitical systems, including their territorializing aspects (Bouzarovski et al., 2015). This is important, as solar energy uptake engages with infrastructure as well as socioeconomic imaginaries of energy (Bridge et al., 2018).

The implementation of new energy infrastructures involves land appropriation, typically in rural areas where power relations favour rapid acquisition, leading McCarthy (2015, p. 2499) to argue 'a thorough overhaul of the energy system could and should provide multiple openings for rethinking, rather than merely reproducing, our political-economic system'. He calls for examining the degree of centralization, ownership and control, and the use-value of energy. Infrastructures transcend technologies as a combination of technical, administrative, and financial techniques (Larkin, 2013), revealing practices of government and biopolitics (Collier, 2011). In Soviet Russia, technocrats advanced electricity supply as part of a system of total planning in a command economy, as opposed to conceptualizing society around the individual. Channelling neoliberal ideology, this

idea was dismantled and reoriented towards individualism (Collier, 2011), a trend echoed in Indian history (Kale, 2014).

Recent energy geographies accounts of energy transitions mainframe socio-material change. Calvert (2016) emphasizes the patterning of energy generation, distribution and consumption as both socio-cultural and material across multiple geographical scales. Tozer (2019) works through the justice effects of strategic material politics, revealing how entrenched energy sector actors act opportunistically even as carbon remains locked into the built environment. Mulvaney (2014) unpacks the metrical representation of material supply chains and lifecycle assessments linked with solar equipment to showcase unjust social effects obfuscated across space. Explicating the links between infrastructure and finance, Furlong (2020) points out that material transitions are co-determined with complex social, cross-sectoral legacies. Such examples demonstrate that the problem is technological appropriation by a growth-oriented global capitalist modality (Ferrari & Chartier, 2018).

Socio-material change can allow for the use of convivial technologies based on 'autonomous individuals satisfying human needs, social solidarity, friendship and mutual giving', and appropriate technologies developed and maintained using local materials and knowledge rather than global supply chains, remote expertise and industrial production (Kerschner et al., 2018, p. 1628). Such energy systems constitute a need-based approach to realizing Decent Living Standards (DLS) that 'facilitate physical and social wellbeing' (Rao et al., 2019, p. 1026). In India, attaining DLS requires more equitable energy distribution. Rajasthan hosts small-scale rural electrification projects conducted by grassroots initiatives like Barefoot College. This institution has electrified nearly 700 villages nationwide – including over 300 in Rajasthan – by embodying principles of equality, collective decision-making, decentralization, self-reliance, austerity, and openness to learning skills. Its support and training of women without a formal education for solar electrification is an inspirational example of female empowerment and electricity access expansion (Mininni, 2022).

Conclusion: the environmental governance of energy transitions

This concludes our case for bridging concepts to enable integrative research on energy transitions governance. Our conceptual operationalization intends to enable closer engagement between theorization and the empirical contexts where scholars must understand and impact non-linear change processes. We posit an approach to solar politics that anticipates multi-scalar low-carbon energy transitions, a rapid shift far beyond the modest changes of the 2010s. Unpacking changes in institutions, accountability and the socio-materiality of the energy sector identifies power inequities, potential systemic transformation, and emerging environmental futures. Such an approach can construct empirically embedded accounts of the stakes for key actors and the political ecologies that modulate energy transitions. We intend to apply these bridging concepts to structure and operationalize empirical study and conceptual advances towards application in the politically-charged settings where such transitions are being governed, contested and implemented.

Specific to the upcoming Rajasthan study, this implies attending to how to synergise climate change responses, electricity access expansion, and the reversal of unjust incumbency relations to address ecological degradation and social fragmentation inflicted by the modality through coloniality (Sultana, 2022), growth (Nirmal & Rocheleau, 2019) and modernity (Arora, 2019). Efforts that acknowledge interrelationships, address inequalities across space and time, and promote conviviality rather than benefiting unjust incumbencies, hold promise. These entail acknowledgment of how incumbency extends beyond institutions to discourse, knowledge and our own imagination

(Stirling, 2019). Incumbency restricts our ability to envision different ways of doing such as the pursuit of DLS and the construction of what Martinez-Alier (1992) refers to as a *concrete utopia,* informed by ecological and scientific views of the economy. A concrete utopia resists the imaginaries of growth while envisioning radical political change, by prioritizing redistribution over expansion (Gómez-Baggethun, 2020).

Our challenge is to unlock such imaginaries. Following Thambinathan and Kinsella (2021), we envision methodological commitment to exercising *reflexivity* by examining our epistemological assumption; *respect for self-determination* by seeking guidance and conducting collaborative research; an *embrace of other(ed) knowledge* through critical evaluation of our theoretical and methodological approaches; and the embodiment of transformative praxis through engagement with questions of wider public benefit. Especially given our positionality as researchers based elsewhere, embroiled in scholarly debates on solar energy transitions and yet with limited opportunity to engage ethnographically with the rural realities of marginality, we see value in such conscious identification of key questions and approaches, with motivation situated in everyday lives and struggles.

Notes

1. We consciously use 'lower-carbon energy infrastructure' rather than 'renewable energy', as the latter framing obfuscates issues around infrastructures built using forced labour, based on toxic lifecycles, still partially reliant on fossil fuels, and implemented without consideration for local ecosystems and inhabitants. 'Renewable energy' is reserved for better socio-ecological cases that use local supply chains and ethical procurement practices to the extent possible, advance community ownership and empowerment, and democratically promote decent living standards within socioecological limits (also see Dunlap (2021)).
2. Nixon (2011, p. 2) describes this form of violence as one that is 'neither spectacular nor instantaneous, but rather incremental and accretive, its calamitous repercussions playing out across a range of temporal scales'.
3. A key leader of India's independence movement and prime minister during 1947–1964.
4. On the one hand, photo-voltaic and concentrated solar power systems can serve off-grid households and village communities (Ulsrud et al., 2015). On the other, even some grid-connected areas experience frequent outages and many households remain unconnected (Martin 2015); in such cases, both types of solar energy systems can supplement existing capacity (Rose et al., 2016).
5. Such as fossil-fuel companies building up significant lower-carbon energy profiles in an effort to reinvent their image, e.g. GDF Suez to Engie in France and Statoil to Equinor in Norway.

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