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frontiers | Frontiers in Human Dynamics

TYPE Mini Review
PUBLISHED 28 February 2024
DOI 10.3389/fhumd.2024.1151614

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OPEN ACCESS

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RECEIVED 26 January 2023
ACCEPTED 09 February 2024
PUBLISHED 28 February 2024

CITATION
Ahlborg H (2024) Technological power, complex systems, and boundary objects in global energy transitions.
Front. Hum. Dyn. 6:1151614.
doi: 10.3389/fhumd.2024.1151614

Technological power, complex systems, and boundary objects in global energy transitions

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This study makes a case for why the field of political ecology (PE) would benefit from deep engagement with technological power, and exemplifies this within the domain of energy studies and the ongoing transformation of the energy sector. Technology is not among the core interests or traditional topics of PE—and is therefore often disregarded or treated as a black box. The argument presented in this study asserts that this omission undermines the analytical power and the relevance of the field. Technology is the central mechanism whereby socionatures evolve and how relationships are negotiated and enacted. The attitude towards technical things is partly based on the idea that technologies are just artefacts of little interest. Cross-field dialogue is also hindered by perceived ontological conflicts. This study draws upon research from the philosophy of technology and sociotechnical systems theory to introduce a dynamic understanding of technological power. Seeing what technology does and has the potential to do requires looking beyond the common emphasis on dominance and control, to the myriad ways in which technologies shape our everyday lives, ontologies, and imagining of the future. Taking on a contentious concept, I advocate for the use of "systems" as a boundary object suitable for cross-field dialogue. As an analytical construct without inherent scale, it works as a framing device for moving power and knowledge claims to the forefront, while also allowing dialogue outside academia.

KEYWORDS

renewable energy, energy futures, power, technology, complex systems, sociomaterial relationships

1 Introduction

The ongoing worldwide transformations of energy systems are of great concern to political ecology (PE) as a field, due to its historical focus on rural–urban relations, land use and politics, inequalities, and environmental change. As a scholar with a background in social environmental science and working in energy sector transformation in the East African region, I interact with multiple fields and regularly engage with PE research. The experience of boundary-crossing technology-oriented studies and PE has kindled my interest in the technological shaping of human–environment interactions. It has also highlighted frictions between communities of social scientists, depending on who they primarily talk to—other social scientists only, natural environmental scientists, or engineers. In the realm of "energy transitions," "nature" is typically treated as a background variable. Conversely, scholars working on "socionatures" or "social–ecological systems" rarely pay attention to technologies (Spivey, 2021). These different communities can learn a great deal from each other. However, there is some friction between the typical framing and studies of interest of the fields. This becomes apparent when one pays attention to boundary-making practices as well as what gets foregrounded and backgrounded in analyses.

In this study, I intend to do three things:

First, I position the discussion at the interface of energy studies and PE and illustrate how energy sector transformation is a concern of PE scholarship, given the expansion in resource extraction, land acquisition, and waste flows that constitute the material preconditions of the transition to renewable energy. There is a relatively small but growing literature that shows how fruitful this exchange already is. While a proper review is beyond the scope of this study, I explore some trends that substantiate my argument that technological power is a frontier for PE.

Second, I provide a sociomaterial understanding of power that frames technology as constitutive to socionature relationships and how these are negotiated and enacted. The main objective of this short introduction is to guide readers who are new to the concept of technological power toward a dynamic view of technology and technological mediation of human–environment relations. I draw attention to the underlying logic of technological arrangements and how these can be altered.

Third, a call is made to engage with systems thinking—a ubiquitous language among engineers and, increasingly, in policy circles. The motivation is twofold: Complex systems thinking enriches an understanding of constitutive power emerging in more-than-human webs. In addition, the language of systems is a valuable tool for communication and cross-field translation. I challenge the common assumption that systems thinking is realist and reductionist. Rather, the system concept places ontology and epistemology at the forefront, bringing healthy attention to the framing of research and providing temporary boundary objects for interdisciplinary dialogue. I conclude by reflecting on the contribution of PE to energy studies and the need to further advance from critique to design.

2 The reorganisation of energy production and use: a frontier of political ecology

Many governments and large international organisations worldwide are attempting to speed up the shift to renewable energy supplies, to reduce the dependency on fossil fuels and its associated risks of climate change, environmental destruction, and geopolitical conflicts. However, the material and energy flows involved in rebuilding core infrastructure in societies and economies presuppose a corresponding expansion in mining and material extraction. Estimates of critical material elements for renewable energy technologies show that projected cumulative demand up to 2050 exceeds the current known reserves of 13 key elements (Calvo and Valero, 2022). The production of solar panels, wind power plants, and electric cars is preceded by excavation that will produce piles of waste in the coming decades. As highlighted by energy geographers and political ecology scholars (Bridge et al., 2013; Kirby, 2015; McCarthy and Thatcher, 2019; Backhouse and Lehmann, 2020; Knuth et al., 2022), the transition to renewable energy involves the acquisition of land and resources on a massive scale, the spatial reorganisation of flows of power (in both senses of the word), money, materials, and people. In this context, governments are looking to consider less populated areas, hinterlands, mountaintops, and coasts as suitable places for large-scale solar and wind generation and as preferred sites for land-extensive mining and waste dumping.

Thus, rural areas (again) represent a frontier of resource extraction under the dominant Western model of production and supply of fuels and electricity, a model based on large-scale infrastructures and centralised state control. However, energy production, supply, and utilization have no inherent optimal scale but are modular and can be economically profitable and technically viable across a range of scales, ranging from micro to small. Localised supply and ownership, including cooperative models, continue to exist in parallel to state monopolies and national grids despite unfavourable institutional environments (Wierling et al., 2018), and the trend towards cross-border transmission and regional energy trading is countered by geopolitical concerns. This means that the dominant energy system model of the future is highly uncertain, and there are many opportunities for various scales of governance, ownership, and practices.

Scholars have identified energy sector transformation as a new frontier for PE (Knuth et al., 2022) and have started to map contributions (Sovacool, 2021). These contributions indicate the diversity and richness of work emerging at the intersection of PE, energy geography, political economy, climate mitigation, and sustainability transitions. Furthermore, they include a wide range of energy sources and technologies. True to its critical theory tradition, studies critique not only the fossil fuel-based energy supply but also the negative impacts associated with "sustainable energy" development (Siamanta and Dunlap, 2019; Dunlap, 2020; Stock and Birkenholtz, 2020; Atkins and Hope, 2021). In the field of energy studies, these contributions are incredibly important for balancing the dominant optimistic accounts of renewable energy development and for challenging the notion that urgency outweighs considerations of justice (Kumar, 2022; Haarstad et al., 2023). Furthermore, energy studies remain dominated by technoeconomic analyses (Newell, 2019), and there is a lack of grounding in critical theory, even in current bodies of literature that label their studies as addressing equity, namely, "energy poverty" and "energy justice" (Ahlborg et al., forthcoming).

Advancements in energy studies are aided by PE. For PE as a field, a value of engaging in the infrastructure-heavy energy sector is that it brings *technological power* into view as a frontier of PE research. A few searches in the Scopus[1] database indicate that PE studies on energy with a technological interest date back to 2010, with four times as many publications in 2023 as in 2015. In December 2023, comparing the number of PE publications[2] to those that mention technology or infrastructure suggests that the latter comprises 13 per cent of the sample. There is approximately a fourfold increase in the number of

1 The search string used on 22 December 2023, was: TITLE-ABS-KEY ("political ecology" AND energy AND technology OR infrastructure OR sociotechnical OR artefact) and generated 98 hits in Scopus.

2 The search string TITLE-ABS-KEY ("political ecology") resulted in 5,322 hits, whereas TITLE-ABS-KEY ("political ecology" AND technology OR infrastructure OR sociotechnical OR artefact) resulted in 726 hits.

publications per year from 2012 to 2022. A third search[3] provides 100 articles that mention both technology and power in their titles, abstracts, or keywords. Despite this, deeper engagements are quite unusual. According to Spivey, PE "still largely lacks a theory of technology" (2021: 1119). Addressing this gap, Spivey builds on a political theory of technology to illustrate its relevance to PE, in an analysis of Japan's power grid. Thus, let me add a stepping stone for further engagement.

3 Technological power

While power is a huge theoretical domain, the following sections will focus on dynamic, relational, and sociomaterial understandings of technological power. Such approaches are adopted within PE (Arboleda, 2016; Stock, 2021; Vaishnava and Baka, 2021; Bruns et al., 2022; Sareen and Shokrgozar, 2022) and align with how socionatures are understood. Relational and sociomaterial approaches are prominent in science and technology studies (STS)[4], which are most clearly formulated in actor–network theory and exist in the highly interdisciplinary realm of "sociotechnical systems" theory, from the historical work of Hughes (1983) to sustainability transitions with its variants based on complex systems theory (Bijker and Law, 1992; van den Bergh et al., 2011; Köhler et al., 2019). However, the language and ontological grounding is different. Thus far, PE scholars have drawn primarily on the STS literature (*cf.* Spivey, 2021; Vaishnava and Baka, 2021). Further resources can be found in the philosophy of technology, where Feenberg (1991) provides an ontology of technology based on critical theory. Meanwhile, Arthur (2009) provides insights into engineering practice and the modular nested nature of technology.

Starting from what technology *is* from a sociotechnical viewpoint, Arthur (2009) provides a working definition of "technology" as a means to fulfil human purposes. The technology in question can be a method, process, or device—often combining software and hardware—used to execute purpos*es* and supply functionalit*ies*. Note that these are plural, as a technological artefact (say, a car) does many things for its owner/user in addition to providing mobility. Technology is socially constituted—thus value laden—but cannot be reduced to values. Feenberg warns us not to conflate "attitude" with "object," the modern obsession with efficiency with technology as such (Feenberg, 1999, p. x).

In this context, technology is understood very tangibly as a purposeful action for exploiting physical phenomena or effects, such as gravity, electric charge, or chemical properties (Arthur, 2009). Humans harness these opportunities in organised and planned ways, which emphasise *practices* by creators, designers, technicians, managers, and users and how these arrangements evolve over time and to what effect. While this sounds like neat engineering, such is seldom the case. Even "simple" technologies tend to jam, break down, and require inventive solutions and continuous care to function properly (de Laet and Mol, 2000).

Mundane technologies work behind the scenes across all economic sectors where these technologies enable production systems, value chains, markets, transactions, communication, usage, and disposal. Technologies enable deep cognitive shifts in our understanding of the world, such as cartography (Avila et al., 2021) and aerospace engineering. These cognitive shifts combine with computer science to enable databases and visual technologies that make land legible as an "asset" to renewable energy investors (McCarthy and Thatcher, 2019). A variety of techno-institutional instruments, claims of expertise, methods, and practices impose conditions and rules that privilege incumbent actors and steer finance their way, ensuring their benefit from renewable energy investments and protection from costs and losses (Sareen, 2021; Spivey, 2021; Vaishnava and Baka, 2021).

Within the sociomaterial family of approaches, there has been some heated debate (Cozza, 2021) around the preferred ontological position, with some viewing "relational or becoming ontology" signalled by the terms "socionatures" and "assemblages" as irreconcilable with "ontology of separateness" that is supposedly inherent in the term "sociotechnical systems" (Hughes, 1983; Orlikowski, 2010). I disagree with essentialist definitions of the terms but find the ontological conflict productive rather than insurmountable and a matter of audience, language, and empirical focus.

From a perspective that keeps humans and non-humans apart, technology constitutes the *interface* in "human–environment"/"society–nature"/"social–ecological systems." If we adopt the "constitutive entanglement" of socionatures, then we *become with and through* technology. Technologies are not just artefacts that we surround ourselves with but a constitutive aspect of our physical and mental capacities. With our bodies and cognition, social standing, and networks, these are *transformed* in a process of becoming and world-making (Braun and Whatmore, 2010).

In either case, I put forward the (perhaps provocative) argument that technology lies at the core of understanding power, central to both *human capacities* to enact change and to the conception of constitutive power as *elusive pressures* emerging out of complex webs of humans and non-humans. Thus, it follows that omitting technology from the framing of "socionature" seriously undermines its analytical capacity. We cannot *decentre* technology because it constitutes the interface and helps shape the *kind* of relationships humans have with their natural environment. Using a different language, technologies are constitutive parties to the collectivities in which we live (Braun and Whatmore, 2010; Cederlöf, 2020). Excluding technology from the frame adopted may render it invisible to the analyst, but its influence on the interactions, feedback, and emergent characteristics remains decisive (Ahlborg et al., 2019).

My understanding of technological power has emerged from exploring energy systems and power in its dual meaning. Energy systems embody the tension between dominance and empowerment, between creation and destruction, and between human agency and constitutive pressures. A relational and practice-orientated account of power (Ahlborg, 2017; Ahlborg and Nightingale, 2018) focuses on tense, productive encounters between people, technologies, and nature. Energy projects are arenas for (and results of) ongoing political struggles where various forms of power are manifested and drawn upon (Newell, 2019; Munro, 2021).

3 The search TITLE-ABS-KEY ("political ecology" AND technology AND power) resulted in 100 hits.

4 A prominent term is "technopolitics," which is somewhat different in connotation from "technological power." The former focuses on the realm of politics while the latter focuses broadly on power relations, including politics. They may be seen as synonymous, depending on how broadly one defines politics.

Our capacity to enact change is enhanced, limited, and radically transformed by technologies of all kinds. However, it fundamentally rests on our acquired ability to harness various forms of energy to do work—and thus "co-constitute the ecological conditions for social life" (Cederlöf, 2020: 82). These sociomaterial arrangements enable other transformative capacities. Technological arrangements are effective in that they stabilise and provide durability to the logic underpinning their design; especially their physical reordering of space creates new territories of power (Juwet and Ryckewaert, 2018). However, new technologies also destabilise social hierarchies and produce ambivalent and unintended outcomes—contestation leaves no design intact (Ahlborg and Nightingale, 2018).

Thus, the dominant forms of techno-institutional arrangements are those that promote top-down control and exploitation. "(W)here society is organised around technology, technological power is the principle [*sic*] form of power in the society. It is realised through designs which narrow the range of interests and concerns that can be represented by the normal functioning of the technology and the institutions which depend on it." (Feenberg, 2005: 49). Power relationships predicated upon dominance and control that are realised by technological design are what Feenberg (2005) calls "technical action," suggesting a one-way direction of cause and effect, in which the subject acted upon lacks a way to reciprocate the action. If we adopt a critical theory position, then this underlying power logic is not only inherent in the technology as such but may also be contested and renegotiated in large-scale arrangements. It may be present in small-scale, localised constellations and thus needs attention.

This foregrounds questions such as: How do we actually, using specific configurations and practices (Shove et al., 2012), establish reciprocal or exploitative relationships in research practice as well as in specific sectors and everyday life? This question is akin to the one relating to what we mean by exploitative or progressive forms of diverse economies (Samers, 2005; Siamanta, 2021), but the analytical lens differs. In engineering terminology, we can *optimise* the system taking different (and plural) considerations into account. What do these evolving constellations, rules, and practices look like?

While these questions highlight human responsibility and agency, the emphasis on design can be misunderstood as a continuation of the control logic. The constitutive conception of power balances ideas of human power through its focus on complex arrangements and encounters, in which a multiplicity of actors and actants shape outcomes. In sociotechnical thinking, complex systems theory offers a language for more-than-human relationships that is understood by social and natural scientists and engineers alike. In energy studies, it works as a tool for translation.

4 Systems and why they make excellent boundary objects

A *system* is composed of interrelated, interdependent components. It has no inherent scale. The scale of observation changes what the system "is." A technical artefact, such as a circuit board, may be viewed as a simple, delimited system, or an individual component of a larger system, such as a computer. Zooming out and up in the hierarchy to computer networks and the internet rapidly brings a shift from *planned* yet *complicated* structures of interacting components to increasingly *complex* sociomaterial constellations.

Coming from, and regularly interacting with, social environmental science communities, I have encountered strong negative reactions to systems thinking. It is true that decision-makers, planners, engineers, and economists often think in terms of systems and that these are sometimes both linear and simplified models, with the ontology reflecting a predictable world in which we (humans/experts) are/should be in control. This reductionist branch of systems thinking is but one of many and is very different from systems thinking that aims for holism, including that which is based on complexity science. Complex systems thinking transgresses multiple disciplines and fields and cannot be subsumed under one ontological and epistemological position. As an umbrella term, it provides certain starting points, including uncertainty and (lack of) control.

Specific and clearly delimited technical systems (such as a nuclear power plant or computer) are premised upon control, which is possible since they are complicated rather than complex, hierarchical and slaved rather than self-organising (Andersson and Törnberg, 2018). These work well within the framework of engineering—until they break down (Bijker and Law, 1992). Complex systems are a different affair. These "systems" are no longer well behaved but display dynamic, uncertain, unsteady, and emergent properties that make them hard/impossible to control. This tension between the complicated and the complex bears a resemblance to the tension between constitutive power and agential power—which allows us to explain why dominance can be so effective and yet suddenly fail.

A first strength of systems thinking is the possibility to maintain hierarchies while decentring humans. If we take our non-human categories (nature and technology) as seriously as human action and treat them as distinct (which systems thinking allows for), then constitutive pressures emerging outside the realm of human agency can become visible to us. For example, we can explore nature–technology interactions (one example being how river sediments and coastal infrastructures interplay in ways unintended and unforeseen by humans (Rogers and Overeem, 2017)) with explanatory power in time and space. In other words, it provides for a more-than-human approach while rejecting a flat ontology—a critique shared by PE scholars (Spivey, 2021; Vaishnava and Baka, 2021).

I suggest that, rather than fixating on whether power is reserved for humans only, the sociotechnical understanding of constitutive power lends attention to the eventfulness, liveliness, and potency of things, without drawing permanent or definite boundaries (the more we learn about the cognition of animals, the communication of plants, and with AI becoming increasingly life-like, the more we may wish to extend our concepts). In short, systems thinking offers a language for difference and causality without assertions of truth.

The second related strength is that systems thinking pushes us to bring the mental frameworks to the fore and clarify the theoretical and methodological choices we make—and negotiate them. Similar to many of my colleagues, I am clear that these are not "systems out there" in the realist sense, but analytical and mental constructs that we use to make sense of the world—and intervene in them. For example, critical systems thinking (Ulrich, 2003), soft systems thinking (Checkland, 2000), and systemic interventionism (Midgley, 2003) focus on reflexivity and learning rather than ontology. They bring epistemological considerations to the fore and the negotiation around meaning and values, treating systems as perceived situations and constructs, not real-world objects.

This bringing to view—visualising assumed structures and relations—and setting of system boundaries that can always be questioned reminds us how the "systems" change as soon as the framing changes. This is humbling and an important reminder to take care in making knowledge claims. It is also the reason that systems make good boundary objects. Systems thinking offers an accessible and visual language for cross-disciplinary and cross-professional negotiation.

Having highlighted the strengths, the limitations should be discussed. Systems thinking has emerged in the Western scientific realm, a fact that has shaped it profoundly (although the non-Western history of mathematics suggests a broader family heritage). Boxes and arrows, technical terms (stocks and flows, components, processes, structure, and function), and preference for abstract figures trigger love or hate reactions. However, systems, similar to "sustainability," are not going anywhere and have profound influence in the world from the political arena to professional practices and legal frameworks. Energy studies and energy development practice, as well as PE and STS, have their roots (and remain firmly grounded) in Western science and colonial knowledge (Schulz, 2017; Mazzone et al., 2023), yet the exchange with decolonial theory focuses the attention on knowledge politics. As systems thinking forefronts the process of framing, it may be pluralised in quite radical ways. It may be worthwhile to explore its boundaries.

5 From critique to creation—another frontier for the critical theory scholar

This study has argued that technological power remains at the periphery of PE, yet is crucial to advancing the field. I suggest that a dynamic sociomaterial understanding of power offers analytical purchase and flexibility across a wide range of studies, scales of observations and geographies, far beyond what I have evidenced here. Locating the discussion at the interface of energy studies and PE, I see that PE can further enrich energy studies through its combination of ontological and epistemological care and plurality, sharp and theoretically grounded analyses of power dynamics, with empirical dedication to real places and people's everyday lives. The dynamic understanding of socionatures provides a sharp contrast with how nature is typically treated in energy studies. I ask PE scholars to take on technologies in an equally dynamic manner.

The short conceptual contribution provided here is merely an entry point to a rich debate covering various strands of sociotechnical studies. It has been provided to spur interest in a closer look at how technologies are part of very specific but unstable arrangements that reproduce or challenge entrenched political interests. Economic and political elites are advancing their claims and interests in the emerging renewable energy sector. They are likely to maintain and extend the current institutionalised logic as much as possible and opt for substitution-only energy sources. Cross-field dialogue and critical theory can challenge the privileging of "efficiency" as a primary value and introduce other and plural values in the design of technologically mediated interfaces. This would disturb dominant frameworks but requires experimentation and attention to detail. Mazzone et al. (2023) propose a "cosmologies-of-energy approach" to radically alter the knowledge politics in energy development projects, while Siamanta (2021: 47) mobilises PE to open the conversation to "multiple possibilities for alternative sustainabilities in a pluriversal world" and takes a productive step from a careful critique to envisioning the intersection between worlds, indicating where we may go next.

PE has a history of engaged research at the community and grassroots level (Knuth et al., 2022). According to Sovacool (2021), the field engages less with policy. I would like to see more studies addressing the cross-scale politics of how techno-institutional arrangements locally and at higher organisational levels can be made to work acceptably (for whom, by whom?) *through* their interaction. Another wish is for complementary attention to the productive and ambivalent expressions of power. While being a "critical PE scholar" stands in sharp contrast to being an engineer "who solves problems," there is a common interest in making things work in the day-to-day lives of ordinary people. To propose, create, design, or build is really to expose oneself. One becomes utterly vulnerable to critique from peers, other professions, and one's community/stakeholders. For a person identifying as a critical theorist, this may be an unsettling frontier.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Funding

The author gratefully acknowledges funding support provided by the Chalmers Gender Initiative for Excellence (Genie) and the Swedish Energy Agency, grant number 2020–22623.

Acknowledgments

The author would like to thank Dr. Muriel Côte and Professor Andrea Nightingale for the discussions that led to this contribution. The ongoing conversation with them has helped shape the argument and influenced the direction taken. Two reviewers also provided their critiques that helped in improving the clarity and arguments substantially.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ahlborg, H. (2017). Towards a conceptualization of power in energy transitions. *Environ. Innov. Soc. Trans.* 25, 122–141. doi: 10.1016/j.eist.2017.01.004

Ahlborg, H., Michael, K., Unsworth, S., Hategekimana, S., Osunmuyiwa, O., Åberg, A., et al. (forthcoming). "*Thirty-five years of research on energy and power: A landscape analysis*"

Ahlborg, H., and Nightingale, A. J. (2018). Theorizing power in political ecology: the where of power in resource governance projects. *J. Polit. Ecol.* 25, 350–425. doi: 10.2458/jpe.v25i1

Ahlborg, H., Ruiz-Mercado, I., Molander, S., and Masera, O. (2019). Bringing technology into social-ecological systems research – motivations for a socio-technical-ecological systems approach. *Sustain. For.* 11:2009. doi: 10.3390/su11072009

Andersson, C., and Törnberg, P. (2018). Wickedness and the anatomy of complexity. *Futures* 95, 118–138. doi: 10.1016/j.futures.2017.11.001

Arboleda, M. (2016). In the nature of the Non-City: expanded infrastructural networks and the political ecology of planetary urbanisation. *Antipode* 48, 233–251. doi: 10.1111/anti.12175

Arthur, B. W. (2009). *The nature of technology. What it is and how it evolves*. New York: Free Press.

Atkins, E., and Hope, J. C. (2021). Contemporary political ecologies of hydropower: insights from Bolivia and Brazil. *J. Polit. Ecol.* 28, 246–265. doi: 10.2458/jpe.2363

Avila, S., Deniau, Y., Sorman, A. H., and McCarthy, J. (2021). (counter)mapping renewables: space, justice, and politics of wind and solar power in Mexico. *Environ. Plan. E: Nat. Space* 5, 1056–1085. doi: 10.1177/25148486211060657

Backhouse, M., and Lehmann, R. (2020). New 'renewable' frontiers: contested palm oil plantations and wind energy projects in Brazil and Mexico. *J. Land Use Sci.* 15, 373–388. doi: 10.1080/1747423X.2019.1648577

Bijker, W. E., and Law, J., eds. (1992). *Shaping technology/building society: Studies in sociotechnical change*. London: The MIT Press.

Braun, B., and Whatmore, S. J. (2010). "The stuff of politics: an introduction" in *Political matter: technoscience, democracy, and public life*. eds. B. Braun and S. J. Whatmore (Minneapolis, London: University of Minnesota Press)

Bridge, G., Bouzarovski, S., Bradshaw, M., and Eyre, N. (2013). Geographies of energy transition: space, place and the low-carbon economy. *Energy Policy* 53, 331–340. doi: 10.1016/j.enpol.2012.10.066

Bruns, A., Meisch, S., Ahmed, A., Meissner, R., and Romero-Lankao, P. (2022). Nexus disrupted: lived realities and the water-energy-food nexus from an infrastructure perspective. *Geoforum* 133, 79–88. doi: 10.1016/j.geoforum.2022.05.007

Calvo, G., and Valero, A. (2022). Strategic mineral resources: availability and future estimations for the renewable energy sector. *Environ. Dev.* 41:100640. doi: 10.1016/j.envdev.2021.100640

Cederlöf, G. (2020). Maintaining power: Decarbonisation and recentralisation in Cuba's energy revolution. *Trans. Inst. Br. Geogr.* 45, 81–94. doi: 10.1111/tran.12330

Checkland, P. (2000). Soft systems methodology: a thirty years retrospective. *Syst. Res. Behav. Sci.* 17, S11–S58. doi: 10.1002/1099-1743(200011)17:1+<::AID-SRES374>3.0.CO;2-O

Cozza, M. (2021). *Key concepts in science and technology studies*. Lund: Studentlitteratur.

de Laet, M., and Mol, A. (2000). The Zimbabwe bush pump: mechanics of a fluid technology. *Soc. Stud. Sci.* 30, 225–263. doi: 10.1177/030631200030002002

Dunlap, A. (2020). Bureaucratic land grabbing for infrastructural colonization: renewable energy, L'Amassada, and resistance in southern France. *Hum. Geogr.* 13, 109–126. doi: 10.1177/1942778620918041

Feenberg, A. (1991). *Critical theory of technology*. New York: Oxford University Press.

Feenberg, A. (1999). *Questioning Technology*. London, UK; New York, NY, USA: Routledge.

Feenberg, A. (2005). Critical theory of technology: an overview. *Tailor. Biotechnol.* 1, 47–64.

Haarstad, H., Grandin, J., Kjærås, K., and Johnson, E. (Eds.) (2023). *Haste: the slow politics of climate urgency*. London: UCL Press.

Hughes, T. P. (1983). *Networks of power: Electrification in western society, 1880–1930*. Baltimore: Johns Hopkins University Press.

Juwet, G., and Ryckewaert, M. (2018). Energy transition in the Nebular City: connecting transition thinking, metabolism studies, and Urban Design. *Sustain. For.* 10:955. doi: 10.3390/su10040955

Kirby, C. (2015). From 'energy geography' to 'energy geographies': perspectives on a fertile academic borderland. *Prog. Hum. Geogr.* 40, 105–125. doi: 10.1177/2F0309132514566343

Knuth, S., Behrsin, I., Levenda, A., and McCarthy, J. (2022). New political ecologies of renewable energy. *Environ. Plan. E: Nat. Space* 5, 997–1013. doi: 10.1177/25148486221108164

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., et al. (2019). An agenda for sustainability transitions research: state of the art and future directions. *Environ. Innov. Soc. Trans.* 31, 1–32. doi: 10.1016/j.eist.2019.01.004

Kumar, A. (2022). Energy geographies in/of the Anthropocene: where now? *Geogr. Compass* 16:e12659. doi: 10.1111/gec3.12659

Mazzone, A., Fulkaxò Cruz, D. K., Tumwebaze, S., Ushigua, M., Trotter, P. A., Carvajal, A. E., et al. (2023). Indigenous cosmologies of energy for a sustainable energy future. *Nat. Energy* 8, 19–29. doi: 10.1038/s41560-022-01121-7

McCarthy, J., and Thatcher, J. (2019). Visualizing new political ecologies: a critical data studies analysis of the World Bank's renewable energy resource mapping initiative. *Geoforum* 102, 242–254. doi: 10.1016/j.geoforum.2017.03.025

Midgley, G. (2003). Science as systemic intervention: some implications of systems thinking and complexity for the philosophy of science. *Syst. Pract. Action Res.* 16, 77–97. doi: 10.1023/A:1022833409353

Munro, P. G. (2021). Energy political ecologies in the South Pacific: the politics of energy transitions in Vanuatu. *Camb. J. Reg. Econ. Soc.* 14, 361–378. doi: 10.1093/cjres/rsab006

Newell, P. (2019). Trasformismo or transformation? The global political economy of energy transitions. *Rev. Int. Polit. Econ.* 26, 25–48. doi: 10.1080/09692290.2018.1511448

Orlikowski, W. J. (2010). The sociomateriality of organisational life: considering technology in management research. *Camb. J. Econ.* 34, 125–141. doi: 10.1093/cje/bep058

Rogers, K. G., and Overeem, I. (2017). Doomed to drown? Sediment dynamics in the human-controlled floodplains of the active Bengal Delta. *Elem. Sci. Anth.* 5:66. doi: 10.1525/elementa.250

Samers, M. (2005). The myopia of "diverse economies", or a critique of the "informal economy". *Antipode* 37, 875–886. doi: 10.1111/j.0066-4812.2005.00537.x

Sareen, S. (2021). Legitimating power: solar energy rollout, sustainability metrics and transition politics. *Environ. Plan. E: Nat. Space* 5, 1014–1034. doi: 10.1177/25148486211024903

Sareen, S., and Shokrgozar, S. (2022). Desert geographies: solar energy governance for just transitions. *Globalizations*, 1–17. doi: 10.1080/14747731.2022.2095116

Schulz, K. A. (2017). Decolonizing political ecology: ontology, technology and 'critical' enchantment. *J. Polit. Ecol.* 24, 125–143. doi: 10.2458/v24i1.20789

Shove, E., Pantzar, M., and Watson, M.. (2012). *The dynamics of social practice: Everyday life and how it changes*. London: SAGE.

Siamanta, Z. C. (2021). Conceptualizing alternatives to contemporary renewable energy development: community renewable energy ecologies (CREE). *J. Polit. Ecol.* 28, 47–69. doi: 10.2458/jpe.2297

Siamanta, Z. C., and Dunlap, A. (2019). Accumulation by wind energy': wind energy development as a capitalist Trojan horse in Crete, Greece and Oaxaca, Mexico. *ACME: Int. J Crit. Geogr.* 18, 925–955.

Sovacool, B. K. (2021). Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Res. Soc. Sci.* 73:101916. doi: 10.1016/j.erss.2021.101916

Spivey, H. (2021). The technopolitics of energy transitions: materiality, expertise, and fixed capital in Japan's power grid disputes. *Environ. Plan. E: Nat. Space* 5, 1106–1122. doi: 10.1177/25148486211006560

Stock, R. (2021). Illuminant intersections: injustice and inequality through electricity and water infrastructures at the Gujarat Solar Park in India. *Energy Res. Soc. Sci.* 82:102309. doi: 10.1016/j.erss.2021.102309

Stock, R., and Birkenholtz, T. (2020). Photons vs. firewood: female (dis)empowerment by solar power in India. *Gender Place Cult.* 27, 1628–1651. doi: 10.1080/0966369X.2020.1811208

Ulrich, W. (2003). Beyond methodology choice: critical systems thinking as critically systemic discourse. *J. Oper. Res. Soc.* 54, 325–342. doi: 10.1057/palgrave.jors.2601518

Vaishnava, S., and Baka, J. (2021). Unruly Mountains: hydropower assemblages and geological surprises in the Indian Himalayas. *Environ. Plan. E: Nat. Space* 5, 1123–1145. doi: 10.1177/25148486211050780

van den Bergh, J. C. J. M., Truffer, B., and Kallis, G. (2011). Environmental innovation and societal transitions: introduction and overview. *Environ. Innov. Soc. Trans.* 1, 1–23. doi: 10.1016/j.eist.2011.04.010

Wierling, A., Schwanitz, V. J., Zeiß, J. P., Bout, C., Candelise, C., Gilcrease, W., et al. (2018). Statistical evidence on the role of energy cooperatives for the energy transition in European countries. *Sustain. For.* 10:3339. doi: 10.3390/su10093339