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Review

Sociotechnical agendas: Reviewing future directions for energy and climate research

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A R T I C L E I N F O

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A B S T R A C T

The field of science and technology studies (STS) has introduced and developed a "sociotechnical" perspective that has been taken up by many disciplines and areas of inquiry. The aims and objectives of this study are threefold: to interrogate which sociotechnical concepts or tools from STS are useful at better understanding energy-related social science, to reflect on prominent themes and topics within those approaches, and to identify current research gaps and directions for the future. To do so, the study builds on a companion project, a systematic analysis of 262 articles published from 2009 to mid-2019 that categorized and reviewed sociotechnical perspectives in energy social science. It identifies future research directions by employing the method of "co-creation" based on the reflections of sixteen prominent researchers in the field in late 2019 and early 2020. Drawing from this co-created synthesis, this study first identifies three main areas of sociotechnical perspectives in energy research (sociotechnical systems, policy, and expertise and publics) with 15 topics and 39 subareas. The study then identifies five main themes for the future development of sociotechnical perspectives in energy research: conditions of systematic change; embedded agency; justice, power, identity and politics; imaginaries and discourses; and public engagement and governance. It also points to the recognized need for pluralism and parallax: for research to show greater attention to demographic and geographical diversity; to stronger research designs; to greater theoretical triangulation; and to more transdisciplinary approaches.

> "The real problem of humanity is the following: we have Paleolithic emotions; medieval institutions; and god-like technology"
>
> E.O. Wilson

1. Introduction

As the quip from the biologist E.O. Wilson provocatively suggests, our rate of technological progress, or at least change, may be outpacing

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our social institutions if not our biological evolution. Even if the veracity of Wilson's statement is cast in doubt, throughout most of our lives, from giving birth to falling ill and even encountering death, we remain intimately connected to technology and the sociotechnical systems in which it is embedded [1–2]. These systems, however, are not static; instead, they change and interact dynamically in often unpredictable ways. Today, there are 12 billion searches on Google every month, and there are more than 8 billion devices connected to the Internet [3]—that is, more devices than people. With 655 million registered Twitter users, if Twitter were a country, it would be the third largest by population in the world after China and India.

Underscoring these trends is the acceleration of sociotechnical change. For example, the first commercial text message was sent in 1992, and now about 400 million text messages are sent daily [4]. It took the radio 38 years to reach 50 million people, television 13 years, the Internet 4 years, and Facebook only 2 years [4]. Moreover, six of the top in-demand jobs in 2010 did not exist in 2004 [4]. Essentially, schools and universities today are preparing students for jobs that do not yet exist, which will employ technologies that have not yet been invented, to solve problems that we have not yet identified. Better understanding the dynamics of this change, as well as what it means for research methodology and practice in the context of climate change and energy transitions, is a potentially overwhelming challenge.

This study begins with the problem of making sense of the interaction or mutual shaping of social forces and technology, the complex ways in which they are co-constituted—with a focus on how these questions matter for interdisciplinary energy social science research. The field of science and technology studies (STS) seeks to provide conceptual and methodological tools for examining the problem. Increasingly, STS perspectives have found their way into social science and policy research on energy, thus adding to existing frameworks that are based in economics, policy studies, sociology, innovation studies, and social psychology. In the process, boundaries between an identifiably "STS" perspective and a broader family of sociotechnical perspectives have become blurred. In this study, we ask the following questions: what can we learn from interdisciplinary research arising from STS and related sociotechnical perspectives when applied to energy studies and related empirical problems such as climate change, and what new research questions emerge for the field of energy social science?

To provide an answer, we explore future directions for STS and sociotechnical perspectives on energy and climate change, or more precisely, at the energy-climate interface or nexus. The aims and objectives of the study are threefold: to map out leading STS and related sociotechnical concepts or tools that are useful at better understanding or interpreting energy and climate change topics; to reflect on prominent themes and topics within those approaches; and to identify research gaps and directions. Based on a novel approach of co-creation (essentially, a richly interdisciplinary co-authorship project in which different authors are assigned sections) with prominent researchers in STS and sustainability transition studies, supplemented with a systematic literature review, we examine three core groupings of relevant work: sociotechnical systems, policy, and expertise and publics. In turn, these three areas involve fifteen distinct topics shown in Fig. 1 (and within them, 39 sub-topics): sociotechnical transitions; social practices and domestication; gender and justice; large technical systems; actors, networks, and heterogeneous systems; transforming innovation; sustainability experiments; governing complex transitions; the politics of design and resilience; disparity and hegemony; public engagement and deliberation; expertise and social construction; expertise and democracy; expectations and hype cycles; and imaginaries and frames. Simply put: sociotechnical research on energy and climate sits within the nexus of these three overlapping spheres at the bottom of Fig. 1.

Perhaps obviously, these conceptual and theoretical literatures and their debates partly overlap, interact, and co-evolve. Nevertheless, they have sufficiently distinct roots—with due implications for their chief concerns, focus and approach—to warrant separate treatment. Also perhaps obviously, not all of the topical areas are equally applied or connected with energy or climate challenges, although all of them are certainly relevant. After introducing this intellectual body of work, we then discuss ways to make STS research more internally rigorous and externally pluralistic and perhaps even more relevant, legitimate, and valid.

2. Conceptual approach and research design

This section conceptualizes STS and the term "sociotechnical" before explaining the rationale for focusing on energy and climate change. It next describes the research strategy for our study, taking special note of co-creation research methodology.

2.1. Conceptualizing STS and the "sociotechnical"

The term "STS" (for "science and technology studies" or "science, technology, and society" studies) is used with a wide range of meanings. In the broadest understanding, STS can refer to any study of science and technology from the perspective of the social sciences and humanities. This understanding of STS includes a wide range of disciplines that do not necessarily explore sociotechnical or societal dimensions, such as philosophical and historical studies that are not concerned with society and rhetorical approaches that focus on language and texts. For STS understood in this very broad sense, there are many research styles or even philosophies of science, with Table 1 presenting one categorization (prone to contestation and disagreement) of some of the variety [5].

Within this broad understanding of STS is a subset of fields that examine the relationship between science, technology, society, and the natural environment. Historically, a distinction was sometimes made, especially among Anglophone researchers, between STS as "science, technology, and society" and as "science and technology studies." [6] The former referred to an approach that was connected with the social movements of the 1960s and 1970s. As an academic enterprise, it involved the use of critical theoretical perspectives connected with the social movements that were used to examine how social institutions (such as the state and industry) and societal inequality affect science and technology and also how scientific and technological change affect society [7–9]. In contrast, science and technology studies referred to an examination of the processes by which scientific knowledge and technological design are constructed and coproduced with social institutions and networks [10]. However, in other languages this distinction between the two meanings of STS is not necessarily maintained, and increasingly the distinction has been superseded by a wide range of frameworks that draw on both research traditions.

In this study we have used the term "sociotechnical" as the general characterization of a family of related approaches to energy research that are influenced by STS but may not all be classified or self-identified as STS. Sociotechnical perspectives date back to research that debunked technological determinism and naïve empiricist accounts of scientific change, both of which assumed that science and technology were somehow set apart from social relations, social institutions, or society [11]. The first STS-inspired sociotechnical perspectives emerged during the 1980s in frameworks such as the social construction of technology, actor-network theory, large technological systems, and the politics of design [7,12]. Sociotechnical perspectives include frameworks used by researchers who identify their work as STS, but we also include under this umbrella some of the frameworks in the related field of sustainability transition studies, where sociotechnical perspectives that drew on STS had an influence on some of the more prominent theoretical frameworks, such as the Multi-Level Perspective [13]. In our understanding, sociotechnical perspectives can also include normative inquiry and research that draws attention to the critical analysis of powerful social institutions that shape the design of technological

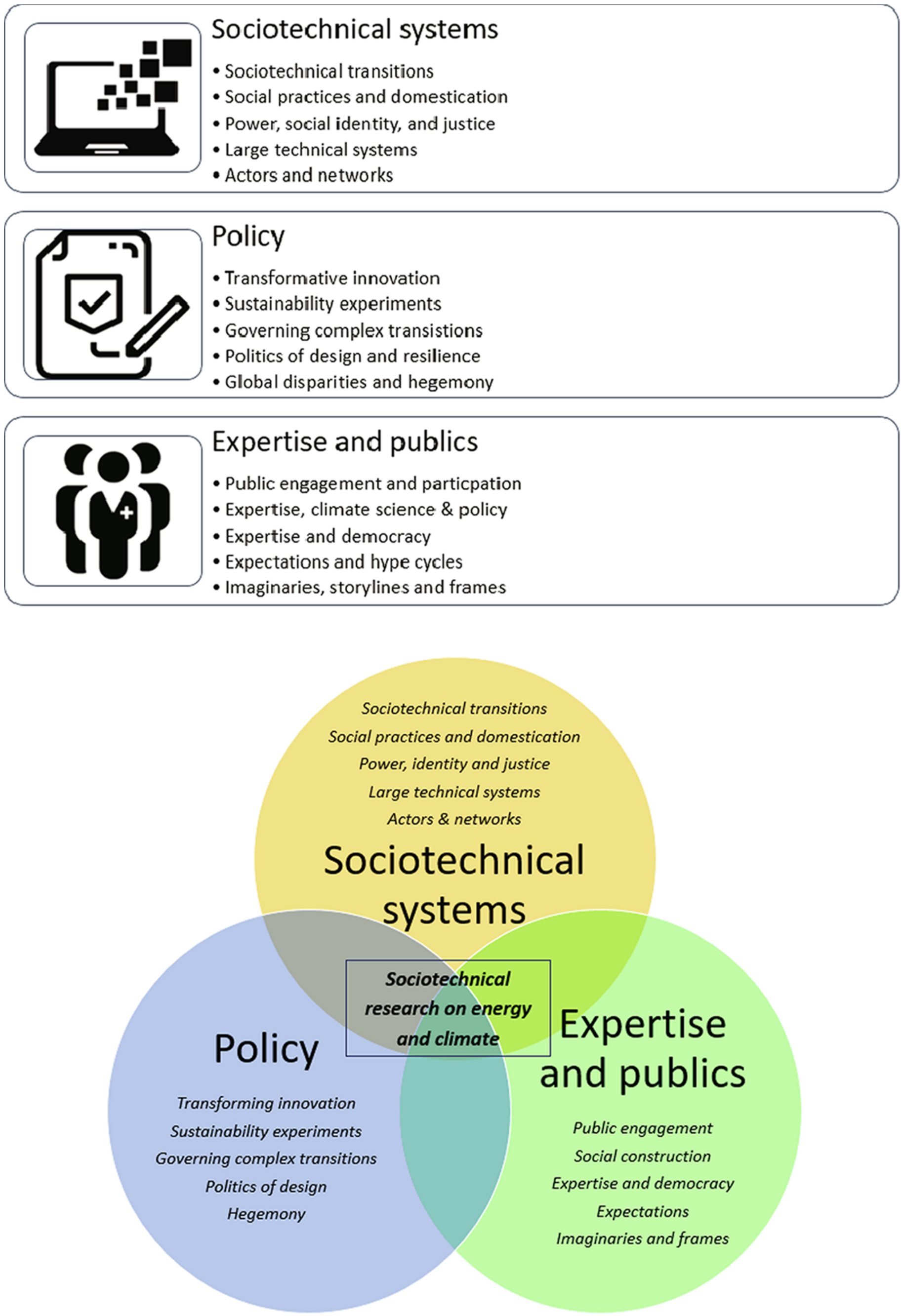


Fig. 1. Overview of main domains and topics of STS energy and climate research. Source: Authors.

systems and the agendas of research fields. There is growing evidence that sociotechnical perspectives have become important in energy social science research—as both analytically more robust but also more impactful— and that a nexus of research has developed at the intersections of STS and energy social science [14–16].

The STS field has grown and diversified substantially since the 1980s. As occurs with most research fields, as STS grew in size and global diversity, it has become much more pluralistic. A companion study reviewed some of the more significant theoretical frameworks and research programs in STS, and Table 1 also offers an overview of some of the underlying theoretical assumptions in the field of energy social science research [16]. (See as well the general classification of underlying assumptions by Abbott.) [17]

2.2. *Justifying a focus on energy and climate*

The use of sociotechnical perspectives in the study of energy is increasingly important because of the rapidity of changing energy systems. These changes connect energy to a wide range of global problems, including social inequality, geopolitical rivalry, economic well-being, pollution, and climate change. Navigating these changes is one of the most complex, demanding, and difficult undertakings humans have ever undertaken [18]. Human societies cannot afford major mistakes in the coming decades. Energy systems are deeply co-produced with human affairs [19], from the daily lived practices and experiences of individuals, households, businesses [20], and national cultural formations and imaginaries [21–23] to global political economies [24], international security [25], and the deep structures of capitalism [26] and democracy [27]. As a consequence, energy is integral to the core functioning of every critical infrastructure: food, water, transport, manufacturing, security, communication, habitation, and more. Energy is at the heart of the most complex relationships of people and technology ever fashioned, which have developed, evolved, and intertwined over centuries. As humans, we are not so much what we eat as how we produce and consume energy in the service of social production and reproduction.

Moreover, the energy transition to lower carbon energy sources is one of, if not the greatest, challenges of our time. As the Intergovernmental Panel on Climate Change makes ever more poignant predictions and as climate activism has grown into a global phenomenon, many governments have not responded adequately to the need for rapid policy intervention. At the same time, a quiet revolution is growing in the world's energy industries. For example, in 2016, solar and wind additions to global electricity supply outpaced coal and natural gas additions [28]. In 2018, the levelized cost of electricity of new solar and wind power plants dropped well below that of building conventional oil, coal, and gas plants to the point that solar and wind became competitive with the marginal cost of operating existing coal and gas plants [29]. The result is a rapid shift in energy economies, investments, regulations, and, perhaps most importantly, imagination [30].

2.3. Research strategy

This study builds on a companion project that was based a systematic literature review of research published 2009 to mid-2019 at the intersections of STS and energy social science [16]. The project was developed from systematic searches in Scopus, the Web of Science Social Science Citation Index, and leading STS journals using the keyword "energy" in combination with "science and technology studies" or "science, technology, and society." The project began with 262 candidate articles and books and selected 68 for inclusion in the review, with more details about its analytical parameters and sampling process explained in [16]. The project also developed a classification of the various types of STS perspectives found in the literature. There were four main groups: discourse, including imaginaries, storylines, fantasies, expectations, and frames; policy, including risk, uncertainty, standards, and performativity; publics, including expertise, engagement, participation, and mobilized publics; and sociotechnical systems, including large technological systems, the politics of design, and users and practices (with actor-network approaches). This project drew attention to the already-existing variety of STS perspectives in energy research and to the potential for the intersection of STS and energy social science to produce new and creative research questions. However, the project was limited in two ways that are addressed in this study: first, it did not include sociotechnical perspectives in sustainability transition studies research, which was treated as a separate field; and second, it did not take the next step of investigating future research questions and agendas that are emerging from this intersection of research fields.

This study builds on the previous project by addressing the issue of emerging agendas and by adopting an open-ended, coauthoring approach. Using the perspectives from the previous project as an initial set of categories of research fields at the intersections of STS and energy social science, the two lead authors identified people in late 2019 who are familiar with STS and sociotechnical perspectives as they apply to energy research and who are knowledgeable enough about a research area to reflect on and write a summary about the area. The main queries for the summary were as follows:

- The STS-related concepts or tools that they viewed as most useful or effective at understanding energy and climate change topics
- Recent research reflecting the core themes or concepts within that topic
- Current research gaps and directions that represented prominent areas of inquiry for the future.

Table 1
One way of representing positivist, post-positivist, relativist, and constructivist assumptions behind energy social science theories.

	Positivism	Post-positivism	Relativism	Constructivism
Assumptions about reality	Reality is independent, objective, empirical and measurable.	Reality is independent and layered, consisting of surface level 'events', mediating mechanisms, and generative structures.	There is no single reality, but multiple stories and narratives of different realities.	Reality is socially constructed through intersubjective meanings.
Explanatory goal and style	Deterministic: uncover general laws and relations between variables (and represent them mathematically).	Interpretive: explain processes by analyzing actions in the context of structures, mediated by causal mechanisms.	Critical: uncover hidden interests and power structures, emancipate the silenced voices, and raise normative questions (on justice, equity and fairness).	Interpretive: describe evolving meanings to understand reality construction.
Common research methods	Experiments, model simulations, manipulation of variables and quantitative data.	Trace processes and event chains (quantitative or qualitative) and attempt to infer causal mechanisms and deeper structures.	Reveal contradictions and paradoxes, show multiplicity and alternatives, open up debates.	"Follow the actors" in real-life contexts, describe interpretations, disagreements and (emerging) consensus.
Typical disciplines	Mainstream economics, social psychology, system analysis and operations sciences.	Structuration theory and neo- institutional theory.	Critical theory, post-structural sociology, critical management studies, critical discourse theory and cultural studies.	Interpretive sociology, phenomenology and social psychology.

Source: Authors, modified from [5].

Importantly, the selection of expert researchers also meant that we could include not only English materials but also relevant materials in other languages, especially Portuguese and Spanish. Unfortunately, not all of the scholars we approached accepted our invitation, and to date the fields of STS, transition studies, and energy social science (and especially their intersections) have a recognized and limited geographical and gender diversity, which some researchers in these fields are attempting to change. These conditions contributed to limitations on the diversity of the author team, and we return to the issue of how to increase the diversity of perspectives in the discussion section. It also means we refrain from calling our review systematic or comprehensive because it reflects only what the co-creators deemed salient enough to include in the scope of the study, it is based on our collective expert judgment. Nonetheless, all of the "co-creators" contributed meaningfully to the evolution of the draft via frequent horizontal interactions throughout late 2019 and early 2020 with the two lead authors and engagement with material across a range of themes and sections (that is, each co-creator was free to comment on other sections beyond their own, for the original co-creator of that section to consider).

This approach can be classified as "co-creation" because we worked with the experts to jointly draft the results section of the study. Over the course of five months, from September 2019 to January 2020, the two lead authors worked with each "co-creator" to draft, revise, sharpen, and finalize their unique section. The co-creation process therefore did involve data gathering, data analysis, drafting, revision, and synthesis. Admittedly, this type of co-creation is more interdisciplinary—between members of different academic disciplines familiar with different conceptual approaches—than *trans*-disciplinary, involving members from non-academic communities. Nonetheless, research on co-creation as a methodology has suggested that it can differ meaningfully across three different domains: timing, scope, and level of collaboration [31–32]. Timing refers to the moment the co-creation takes place: at the beginning, middle or end of the design or research process, or even in the phase of use. Scope refers to the amount of direct benefit or change there is for a co-creator or user. Level of collaboration refers to the extent of meaningful cooperation between the involved parties. Our approach falls in the upper right quadrant of this spectrum in Fig. 2—for being inclusive, beneficial, and collaborative—because we involved our experts at the beginning of the research process; established clear benefits for their participation (authorship on the paper); and depended on them to actually lead the crafting of each of their fifteen subsections.

This model was used successfully in a similar project published by the Sustainability Transitions Research Network [33], and a version of the method is also used in reports of the Intergovernmental Panel on Climate Change [34]. The STRN project is particularly notable as it also opened up its research agenda to critical commentary from additional authors/creators [35–37], something we intend to do at a later stage. In this study, the method involves a first draft of the contribution of the section by each of the authors, followed by review and comments by the two lead authors, a redraft of the sections, the first draft of the entire document prepared by the lead authors, a redraft of the document based on internal review, and then external peer review.

Drawing on the perspectives identified in the prior research project, this study began with three broad areas where sociotechnical perspectives are prominent in energy research: (1) sociotechnical systems, (2) policy, and (3) expertise and publics. (The fourth category, discourse, was subsumed in the third area of expertise and publics.) Admittedly, some adjustments were made as this study developed. First, as we solicited participation, we shifted the subtopics within these three broad areas based on what the researchers thought were the best ways to conceptualize the subtopics. Second, consistent with the interest in "sociotechnical" perspectives, we included several discussions at the intersection of STS, innovation studies, and sustainability transition studies. This is because STS was an important thread in the development of sustainability transition studies and because of the importance of sociotechnical perspectives in these related fields. Third, to ensure more diversity than was identified in the prior systematic review (a limitation in the existing literature that we return to in the discussion section), we invited additional sections that discussed gender and justice and that were written by STS researchers located outside the North Atlantic region. These adjustments resulted in a final set of 15 topics within the three broad or general categories. The three broad categories are then described respectively in Sections 3, 4, and 5 (See Table 2).

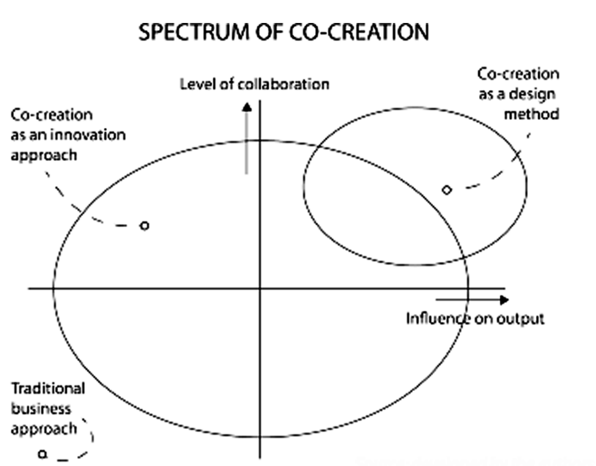


Fig. 2. A spectrum of co-creation research methodology. Source: [32].

3. The salience of sociotechnical systems

In this section, we begin to present the results of the co-creation exercise, the cluster of STS work identified as most salient around the category of sociotechnical systems. This involves five topics: sociotechnical transitions; social practices and domestication; power, gender, and justice; large technical systems; and actors and networks. Because sociotechnical transitions research has grown into such a large field, it is longer than the other sections.

3.1. Sociotechnical transitions

Research on sociotechnical transitions has expanded, diversified, and deepened since 2010, and the Multi-Level Perspective (MLP) has become a core framework to analyze transformative changes in energy, buildings, mobility, and agri-food systems [33,38]. These systems consist of multiple heterogeneous elements that are linked together to fulfil societal functions like mobility, sustenance, lighting, and heating. While Fig. 3 provides a schematic representation of sociotechnical systems, the precise configuration or architecture of these elements varies between different systems. As public concerns about the urgency of climate change mitigation are heating up and as some radical low-carbon innovations are moving beyond early niches (a term to describe novel or emerging innovations), the following four topics are likely to become more pertinent in MLP-based research.

3.1.1. Diffusion of low-carbon innovations

The first topic is the diffusion of low-carbon innovations. Because economic and psychological adoption models, which have come to dominate the diffusion literature, focus on factors that shape consumer purchase decisions, they insufficiently address other issues such as social acceptance (which affects onshore wind, carbon-capture-and-storage, nuclear power, biomass combustion, and smart meters in many countries), business involvement in the construction of new systems (like district heating or trams), or the role of policymakers in shaping selection environments. Adoption models should therefore be complemented with sociotechnical approaches to diffusion [40] such as

Table 2
Summary of perspectives, topics, and subtopics of STS energy and climate research.

General category	Topic	Section Author(s)	Subtopic
Sociotechnical systems (Section 3)	3.1 Sociotechnical transitions	Frank W. Geels	1. Diffusion of low-carbon innovations 2. Acceleration of low-carbon transitions 3. Whole systems transitions 4. Dynamics of problems and solutions
	3.2 Social practices and domestication	Marianne Ryghaug	5. Social practice approaches 6. Domestication and mutual shaping
	3.3 Power, gender and justice	Jennie Stephens	7. Wealth and power 8. Gender and patriarchy 9. Justice and elites
	3.4 Large technical systems	Erik van der Vleuten and Richard Hirsh	10. System building 11. Phases and momentum 12. Technological stasis
	3.5 Actors, networks, and heterogeneous systems	Antti Silvast	13. Actor-network theory 14. The sociology and anthropology of infrastructure
Policy (Section 4)	4.1 Transforming innovation	Johan Schot and Carla Alvial Palavicino	15. Constructive technology assessment 16. Responsible research and innovation 17. Transformative innovation policy
	4.2 Sustainability experiments	Bruno Turnheim	18. Variety of sociotechnical experiments 19. Variety of motives for experimenting 20. Transformation-oriented experimentation 21. Strategic niche management
	4.3 Governing complex transitions	Clark Miller	22. Governing processes 23. Governing outcomes 24. Governing futures
	4.4 Politics of design and resilience	Sulfikar Amir	25. Comparative politics of technology 26. Risk and resilience
	4.5 Global disparities and hegemony	Leandro Rodriguez Medina	27. Asymmetry and marginalization 28. Hegemony in a world of low ontological complexity 29. Hegemony in a world of high ontological complexity
Expertise and publics (Section 5)	5.1 Public engagement and deliberation	Roopali Phadke	30. Downstream and upstream engagement 31. Changing the dynamics of engagement
	5.2 Expertise, climate science and policy	Steven Yearley	32. The construction of climate knowledge 33. Climate denialism and competing problem constructions
	5.3 Expertise and democracy	Andy Stirling	34. Cockpit-ism 35. Transdisciplinary action research
	5.4 Expectations and hype cycles	Harro van Lente	36. Visions and anticipation 37. Entrenchment
	5.5 Imaginaries, storylines and frames	David Hess	38. Imaginaries 39. Storylines and frames

Source: Authors

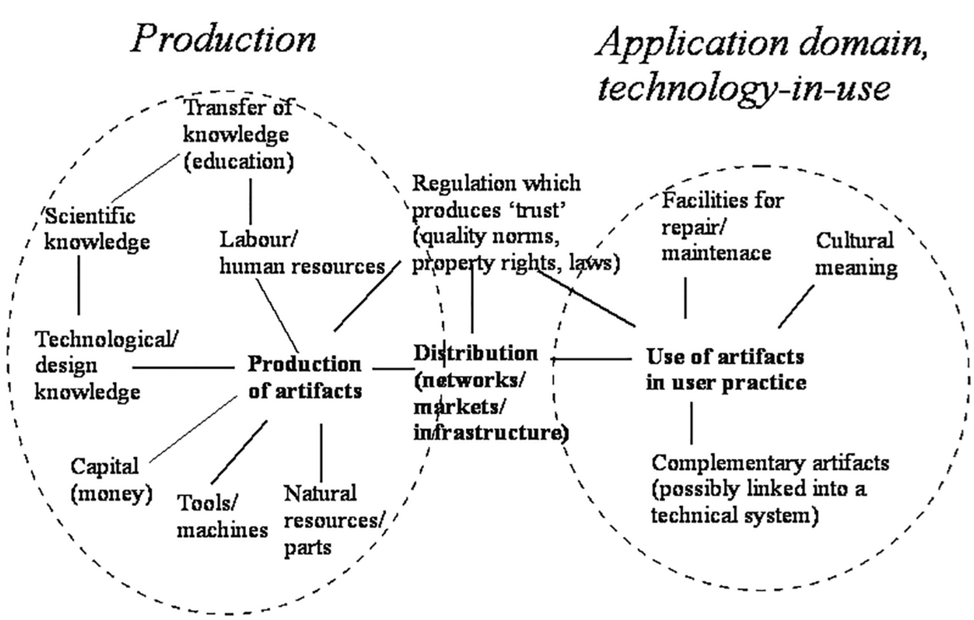


Fig. 3. Basic elements of sociotechnical systems. Source: [39], used with permission.

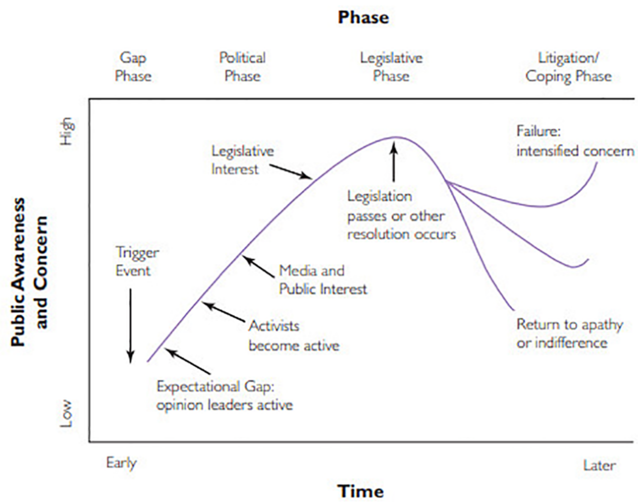


Fig. 4. Temporal dynamics of issue lifecycles. Source: *(Rivoli and Waddock, 2011: 91)* [68].

Hughesian system building theories [See 3.4], circulation and replication models [See 3.5], or the societal embedding approach. The latter conceptualizes diffusion as an alignment process between the niche-innovation and wider contexts (including existing regimes). Because of its processual orientation, the societal embedding approach does not conceptualize external contexts as "barriers", but as dynamic environments that can (partially) be shaped. Geels and Johnson [40] distinguish four processes of societal embedding of innovations: cultural appropriation (including discursive and framing struggles) [See 5.5], regulatory embedding (including political struggles over regulations and standards) [See 4.3], embedding in the business environment (including business strategies and strategic games), and embedding in user environments (which involves not just purchase, but also appropriation and domestication [see 3.2]). Kanger et al. [41] applied this framework to the diffusion of electric vehicles, while Mylan et al. [42] used it to analyze multi-dimensional struggles between plant-based milk and the existing dairy regime.

3.1.2. Acceleration of low-carbon transitions

In 2018, the International Energy Agency [43] found that only four out of 38 clean-energy technologies were on track to meet long-term climate targets. Besides solar-PV, electric vehicles, LEDs, and data centers, there are thus not yet many examples of acceleration. Scholars therefore also investigated acceleration in historical transitions: Sovacool [44] analyzed ten rapid transitions, while Roberts and Geels [45–46] studied four system transitions. The following factors have been identified as drivers of accelerated transitions:

- Landscape level: a) external shocks (e.g. wars, oil shocks) that disrupt existing regimes, and b) gradual trends (e.g. increasing purchasing power) that create fertile grounds for uptake and diffusion.
- Niche level: a) expansion of coalitions, including NGOs and firms, which increases financial, technical and political resources [47–48], b) positive discourses and visions that appeal to mass publics [49–51], c) rapid technological improvements and cost reductions [52], and d) major policy changes that alter selection environments [53], e.g. financial incentives, regulatory standards, infrastructure investments.
- Regime level: a) regime destabilization that weakens the resistance potential from incumbent actors, [54–56] and b) defection of incumbent actors towards niche-innovation [45,57].

3.1.3. Whole systems transitions

Although sociotechnical transition research is interested in system change, many publications have focused on singular niche-innovations like solar-PV, wind turbines, electric vehicles or community energy. These studies represent a "point source" approach, which conceptualizes transitions as bottom-up disruptive processes. Research of whole system transition, however, requires a broader approach that simultaneously analyses multiple niche-innovations (including business model and social innovations) and multiple (sub)regimes [58–59]. Instead of singular disruption, whole system transition is seen as a gradual reconfiguration process that arises from multiple interacting change processes such as:

- niche-innovations that substitute system components (e.g. renewables replacing coal-fired power plants)
- niche-innovations that are incorporated in existing systems (e.g. smart meters, biomass combustion in converted coal-fired power plants)
- niche-innovations that help align separate regimes (e.g. smart cards facilitating intermodal transport systems)
- component substitutions in one sub-regime that affect other sub-regimes (e.g. intermittent renewable electricity generation has knock-on effects on electricity networks)
- changing functional relations between sub-regimes (e.g. demand-side response implies a change from the current "supply-follows-demand" principle to a "demand-follows-(intermittent)-supply" principle)
- changing size of competing regimes (e.g. modal shift from cars to public transport).

3.1.4. Dynamics of problems and solutions

The fourth topic is the dynamics of problems or issues, and how these influence the selection environment in which niche and regime innovations interact. Problems like climate change need to be articulated, defined, and placed on agendas in order to be addressed by policymakers, consumers or firms. Sociologists have long investigated the dynamics of framing and problem definition [60–61], which remain important research topics since the meaning of problems may affect the sense of urgency (e.g. "climate change" vs. "climate emergency") [See 5.4, 5.5]. Business and society scholars further developed issue lifecycle models [62], which suggest that problems start their career when actors identify a gap between perceived and desired states (see Fig. 4). Protests or activist campaigns may then increase public and media attention to the issue, which may subsequently trigger interests from policymakers. Policymakers may then set up committees to analyze the problem and explore potential solutions. If attention remains high, they may introduce legislation that alters the selection environment or implements a particular solution. The policy may address the problem, but it is also possible that implementation fails (or is seen as too costly), which could either trigger renewed concern and activism or lead to apathy, when the public loses interest in the problem [63]. Climate change has experienced several issue-attention cycles in the past 30 years [64], and there is no guarantee that the current attention upswing will be the last one. One reason is that other societal problems (e.g. health care, pensions, education, poverty, security) compete for scarce attention [65], which means that the focal issue of climate change may not remain very high on agendas for long. Another reason is that vested interests try to prevent decisive actions by downplaying the climate change problem [66], by lobbying or advocating incremental solutions that are unlikely to solve the problem [64]. On the other hand, niche advocates are pushing their radical innovations as potential solutions to climate change. The coupling of these solutions with high public attention and political windows of opportunity may (at certain times and in particular sectors and countries) lead to substantial policy actions [67] that substantially change selection environments and advance transitions [see 5.4].

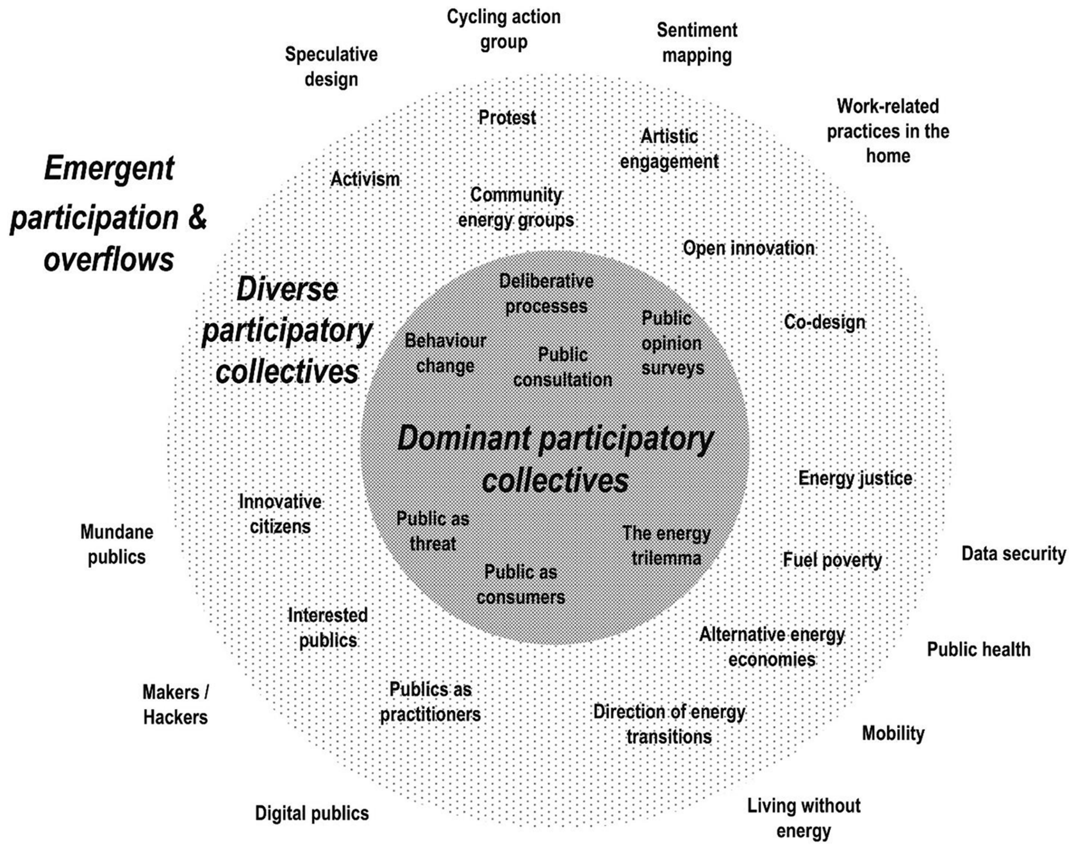


Fig. 5. Mapping participatory collectives and ecologies of participation in the United Kingdom energy system. Source: [98].

3.1.5. Future directions

Firstly, further systematization of the integrative framework of societal embedding could benefit from more empirical studies and conceptual elaborations. Second, in terms of accelerating transitions, the crucial issue now is to better understand how the various factors interact in conjunctural or configurational causal packages [69]. A promising research stream on sequencing and positive feedbacks has started to investigate the interacting acceleration mechanisms and recurring patterns in the context of low-carbon transitions [70–73]. Thirdly, research of whole system transitions not only opens up new questions, but also speaks directly to the IPCC's [74] call for rapid and far-reaching "system transitions" in energy, transport, food, buildings, and industry. Lastly, the dynamics of problems and their coupling with solutions has not yet received much attention in sociotechnical transitions research. But to understand the directionality and speed of transitions, it is an important research topic that can be investigated from many interesting angles.

3.2. Social practices and domestication

STS and sociotechnical research recognize that focusing on individuals and individual behavior may not lead to the widespread societal change needed to decarbonize societies. However, social practices do represent an important aspect of sociotechnical change, and research.

3.2.1. Social practice approaches

Social practice approaches move away from focusing on energy use as an individual choice towards considering social practices to be the central unit of analysis and enquiry. Social practice approaches acknowledge that energy-related practices are constituted through and embedded in society and shaped by culture and meanings, materials and technologies, institutions, and infrastructures [75–76]. Routines and habits are important parts of sociotechnical systems, alongside technologies, infrastructures, maintenance, policy and regulations [39]. At the same time, people incorporate sociotechnical systems and technologies into their routines, practices and everyday life. Practice-focused studies have expanded its conceptual repertoire and explored new empirical terrain over the last years [77]. Later developments not only focus on end consumers and take typical activities such as retrofitting, cooking or cleaning into consideration, but they also have been more focused on professional practices [78], climate policy and environmental politics, and how infrastructures and practices are woven together [79].

3.2.2. Domestication and mutual shaping

STS has shown how technologies and technology users mutually shape each other in technology production and in everyday life. STS scholars who probe technology production, design, or deployment have explored how technology and energy system designers imagine publics, laypersons, and script technologies and through this build assumptions about technology users into technology design, systems, or policies. (See, e.g. [80–84]). From a user perspective, user-technology relationships can be described as domestication [85–86]. This perspective recognizes that technologies are not stable and immutable, but must align with pre-existing routines, practice, identities, and values as they are adapted to household situations, and as they, in turn, influence pre-existing household dynamics [87–88].

These long-standing topics of STS inquiry have over the last years been echoed within energy and climate research in the social sciences and humanities [89]. The envisioned roles of "energy users" have shifted from being passive customers, consumers, or users to being active participants in energy transitions. First, several studies illustrate how energy technologies are increasingly situated close to domestic everyday life and can change engagements with them [90]. Examples include PV solar panels [91], batteries [92], electric vehicles [88], energy-use feedback systems [93], and wider energy community initiatives [94]. Including and involving diverse publics in decision making is increasingly seen as important to the success of energy and climate transitions, in the academic and policy sense and in the view of research funding agencies [95]. [See 3.3, 5.1]

3.2.3. Future research

These developments have also resulted in important future directions and conceptual frameworks for sociotechnical perspectives on energy and climate research: an object-oriented ontology with a focus on material participation and focus on "collective participatory practices" or "ecologies of participation" (see Fig. 5). First, object-oriented perspectives, like the theory of "material participation," highlight how introducing and using emergent energy technologies may create new ways of engaging in energy and climate issues [90,96]. [See 5.1.] Analysis of the ongoing introduction of new material objects have highlighted how these technologies can be seen as material interventions co-constructing temporalities of sustainable practices, and how artefacts such as the electric car, the smart meter and PV may become objects of engagement that foster energy citizenship [97]. These processes include the domestic sphere but extend beyond them to communities, cities, regions, and even wider political systems. Future directions will need to develop our understanding of how to make larger systems that cater for these collective processes of material participation.

Second, there has been a move toward a perspective that sees people as active participants of the energy transition [95]. [See 3.5, 4.1, 5.3] This perspective dates back to the attention to the agency of laypeople in Wynne's work on the public understanding of science in the case of nuclear energy exposure in the U.K. [99–100]. This has led to dispersed sets of strategies to institutionalize public engagement and efforts to organize direct engagement of publics in projects and research, typically through dialogic processes and forms of participation such as citizen science [101], co-design [102], and social innovation, where publics take on active roles. However, STS scholars have recently criticized these directions for staging participation through isolated events where "the public" is framed too narrowly, assuming publics are out there and waiting to be discovered [103–104]. Future directions need to move beyond such understandings to reimagine and remake participation in science and technology development in a way that sees participation as more open-ended process that does not happen at particular events or moments. Rather, participation is orchestrated across different arenas of society [105–106].

3.3. Power, identity, and justice

More research is needed to reveal and understand how social systems that perpetuate inequities of race, income, gender, and other demographic attributes, and the oppression of marginalized people and communities, are connected to climate and energy. Inequities are distinct from inequalities; inequalities refer to uneven distribution, whereas inequities refer explicitly to unjust, avoidable differences resulting from exclusion or poor governance. Research on race, income, gender, and social justice can be done in any context around the world, although the power dynamics of poverty, racial disparities and gender inequities play out differently in different countries and regions of the world. Recognizing this, the descriptions below are based primarily on a North American and European context with the United States being the country with the most extreme recent shift in the concentration of wealth and power. Racial inequities in the United States are also particularly challenging due to the legacy of slavery and the subsequent mass incarceration of black Americans.

3.3.1. Wealth and power

This stream of research explores how the concentration of wealth and power has influenced climate and energy policy and discourse. The concentration of wealth and power that has taken place in the past 40 years reflects societal systems in which rich powerful male-dominated elites profit from (a) increased precarity of people and communities and (b) the license to pollute [107–109]. More research connecting the predatory practices of the polluter elite with climate and energy is needed. Additional research on how polluter elites influence government subsidies of energy, weaken environmental regulations in favor of fossil fuels, and resist socio-technical change would be valuable. Research in this area has potential to be impactful by contributing to destabilizing the power of these elites and by providing additional analysis to justify the growing social movement calling for large sociotechnical transformation simultaneously to mitigate climate change, to transition from a fossil fuels-based society to a renewables-based society, and to redistribute and diversify power to improve the lives of marginalized people and communities. Building on the work of Kenner, Oreskes, Frumhoff, and others who document corporate strategies and link elite behavior with climate impacts, [108,110–112] racial and gendered analysis would contribute not only an additional critical dimension to understanding how the concentration of wealth and power is linked to systems of oppression but also a better understanding of climate action and energy transformation. Analysis of temporal changes in the distribution of wealth, the distribution of climate emissions, the distribution of fossil-fuel subsidies, and the distribution of climate impacts could enhance understanding of linkages among racial injustice, economic injustice, health disparities, climate justice, and energy justice [See also 5.3].

3.3.2. Gender, racism and patriarchy

This strand explores how climate and energy investments, decision-making, policy, and research have been dominated by patriarchal systems that privilege the voices and power of white men over women or people who are not white. Climate and energy investments, decision-making, policy, and research have also focused more on technological innovation rather than social innovation, which is related to the gendered realities of who is setting the research agenda. To balance the focus on research focused on technological innovations, more research is needed on a broad spectrum of potential social innovations to overcome the social lock-in – this includes research on policy innovations (i.e. adjusting subsidies, Green New Deal, restricting corporate influence on policy), economic innovations (i.e. cooperative ownership, taxing the polluter elites, finance practice), institutional innovations (i.e. electric utilities, cooperative and community energy), educational innovations (i.e. impact of climate-energy curriculum, job training) and cultural innovations (i.e. sustainable consumption related to food, fashion, consumer goods, etc.) [See 4.3, 5.1].

More research is also needed on how different communities are responding to climate change and being included in or excluded from energy innovations, and more research is needed on how energy systems are co-designed and co-developed in partnership with communities. Research exploring the social dynamics of power imbalances, representation, and the demographics of climate and energy leadership over time in these different areas at different scales (i.e. investments, policy proposals, technology proposals, technological innovation, social innovation, etc.) could highlight the value of diversifying climate and energy leadership. Likewise, research documenting how diversity and inclusion in climate and energy, and linkages with social justice and racial justice (i.e. the work of Myles Lennon that connects with the Black Lives Matter movement [117]), have led to different kinds of proposed initiatives, proposed investments, and social innovations [118]. More of this research would also inspire and motivate a broader set of constituents and communities, and in doing so it could expand the inclusivity of who is involved in setting the agenda for climate and energy research.

3.3.3. Justice and elites

With growing inequities and the concentration of wealth, elites have new and different power influencing society, including the climate and energy agendas [113]. Philanthropic money is driving more of the climate and energy research and action agenda, and corporate interests are also increasing their influence. Elites can also capture and co-opt energy and climate pathways such as climate adaptation [119], renewable energy auctions [114], or disaster recovery programs [120] to suit their needs. More reflexive inquiry on the role of elites in climate and energy agenda setting would be valuable [115–116]. This could include research on how researchers can have a greater impact on what is happening and how researchers are influencing (or benefiting from or resisting) philanthropic or corporate priorities. With the decline of the mainstream media in many countries, some academics are stepping up and getting involved in new ways of communicating their research beyond the academic literature.

3.3.4. Future research

For wealth and power, specific areas of research could include racial and gendered analysis of fossil fuel corporate strategies over time. For example, in the U.S., the National Association for the Advancement of Colored People (NAACP) produced a report on fossil-fuel tactics targeting black communities [121]. Research could also examine misogyny in climate and energy discourse such as hatred expressed toward powerful young women who propose changes that threaten the status quo. Racial and gendered analysis could also include the growth of social movements, such as the youth climate strike, and climate-change coalitions. Research questions could include the following: How have the demographics of climate and energy leadership shifted over time? Future research on various aspects of climate and energy leadership would improve understanding of the power structures of who is included and excluded in energy and climate decision-making. How can research better explore, understand and promote institutional and financial innovations? How are changes in energy and climate jobs and employment impacting different communities and disadvantaged communities? How are racial and gender disparities being impacted?[122] How are energy systems, both legacy systems and new renewable configurations, impacting women's empowerment and violence against women and girls?[123] For elites and justice, as the pace of change is accelerating, what are some innovative ways that academic researchers are engaging differently? How are relationships among researchers, philanthropy, and corporate interests evolving? How can research and researchers connect more directly with growing social movements for climate action (climate strike) and renewable transformation?[124]

3.4. Large technical systems and energy

Large Technical System (LTS) studies developed from the 1980s onward as a set of concepts and narratives scrutinizing the history, dynamics, and socioecological implications of sociotechnical systems, with a particular focus on infrastructure and production systems. Energy systems figured prominently from the outset. The emblematic case of electricity system development [125] demonstrated the field's endeavor to (1) take as the unit of technology analysis not highly visible artifacts (such as the hydroelectric dam, light bulb, or electric motor), but the "system" of electricity provision consisting of interacting technical, social and environmental "elements" (energy sources, generators, distribution grids, regulations, companies, user practices, etc.); and (2) conceptualize the role of actors and *agency* in making and changing such pivotal societal (infra)*structures*. Later studies included more complex "systems of systems" or "second-order" systems [126], the elements of which are controlled or governed by very different agents, institutions and rules: these include transnational coal, oil, or nuclear-based energy systems but also knowledge infrastructure systems, e.g. for climate modeling [127]. Thematically, the LTS field studied the dynamics, governance, risks, sustainability, inequalities, and Europeanization of those systems, amongst others [128–134]. The LTS notion of socio-technical systems informed diverse literatures including early transition theory [see 3.1] [135], urban studies [136–137], and infrastructure studies [138]. Some refer to the continued relevance and impact of this classic sociotechnical approach a "theoretical shock of the old." [139]

3.4.1. System building

LTS concepts were designed as sensitizing concepts—not to be strictly defined or to model system evolution, but to open-up investigation of the messy complexity of sociotechnical change across conventional scholarly divides—notably socio-technical, agency-structure, (trans)national, and inter-system divides [140]. For example, the concept of "system building" invited researchers to identify actors who perceive energy *systems* (rather than specific elements or interests), and to interrogate how such actors manipulate and align technical, social, and environmental elements into a functioning structure. Often this proved a quite unplanned and pragmatic process of articulating and attempting to solve technical and social "critical problems" hampering system development [141]. The same goes for negotiating local, regional, national, and international energy system elements in transnational system building [142], and for inter-system "gateway building" [143] or "system entangling." [144] The notion of "border building" highlights that system building may also involve material, institutional or discursive boundary work (e.g. Frontex building the EUROSUR system to intercept illegal migrants to Europe) [145].

Later LTS authors conceptualize system building as a distributed, highly contested, and open-ended multi-actor game that cannot be adequately captured from a single theoretical or actor perspective and should be studied empirically at multiple sites and scales [see also 3.5] [146]. Still, for methodological reasons it remains productive to mimic older research and study selected individuals or organizations as system builders, e.g., to query how renewable energy entrepreneurs' engagement with critical problems and conflicts (often between different actors involved, such as haves and have-nots, insiders and outsiders, niche players and incumbents) shapes energy system change [147], or how energy companies use system engineering and other tools to make strategic and operational decisions [148].

3.4.2. Phases and momentum

As systems grow in size and complexity, they increasingly exceed the capacity for reflexive action of even the most centrally positioned actors [149]. Several structure-level concepts therefore guide the inquiry of how, as a result of multiple complex interacting actor and system processes, LTSs develop through overlapping phases of invention, expansion, growth, gaining momentum, transfer and adaptation to other contexts (expressed in situated "styles"), system contestation and reconfiguration, and stagnation and decline [150]. Of particular relevance is the concept of momentum—denoting the "mass" of interacting and interlocked social and technical elements evolving in a certain "direction" with a certain "speed" —as well as notions of challenging momentum and system reconfiguration through various system transition pathways [see 3.1] [13,151]. Transnational and inter-system dynamics can further reinforce the momentum of fossil fuel-based energy systems, but also—thanks to the same interconnectedness of system elements that produces momentum and lock-in—ignite chain reactions of change [152].

Since reconfiguration processes may depend on specific properties of a LTS (such as the degree of tight-coupledness of elements, the materiality of the links, or the form of governance), some have worked on LTS typologies and properties [153]. Older, mature LTSs can also undergo reconfiguration (when the system adapts to challenges but control remains mostly stable), contestation (the system is in limbo as control is challenged), and stagnation and decline (system growth erodes, quality of service or volume deteriorates, control over system is lost) (See Fig. 6).

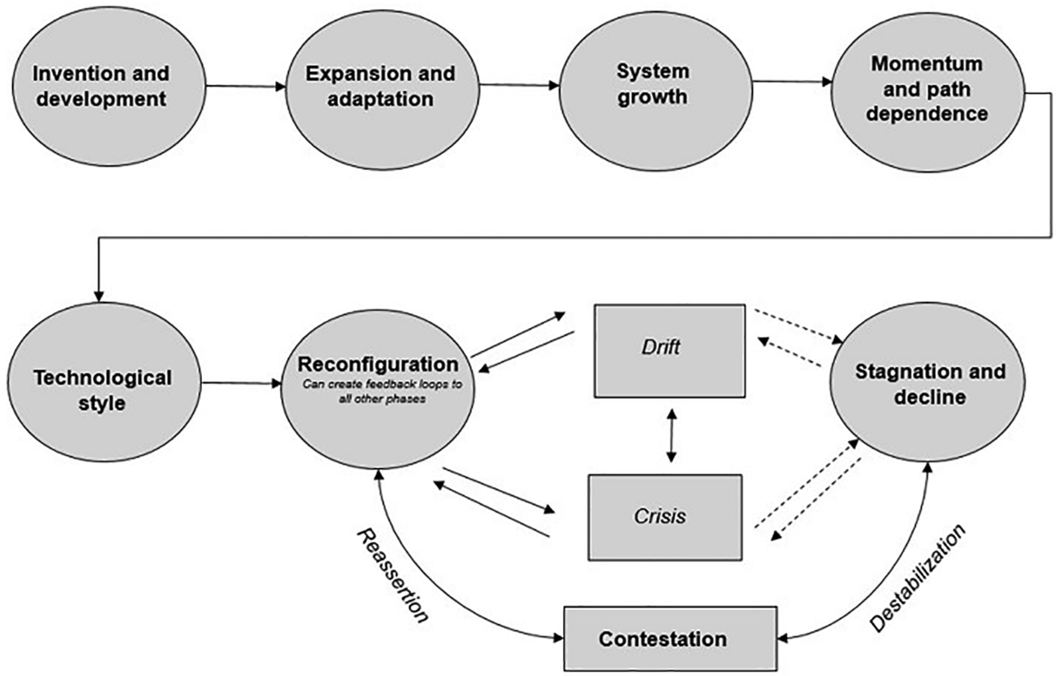


Fig. 6. Phases of Large Technical System (LTS) Development from Invention to Decline. Source: [155].

3.4.3. Technological stasis

Technological stasis refers to the apparent end of long-term, positively-viewed trends in technology, exemplified by the case of hardware involved in making electric power. In the 1960s, the thermal efficiencies in steam-turbine generators ended their pattern of ongoing improvement, and a decade later, the scale of power producing units abruptly plateaued. Both factors seemed to terminate a more-than-six-decade period of incremental improvements that contributed to making electricity a low-cost and abundantly available commodity [154]. Some of the driving forces to stasis were technical, but other problems remained inherently social, such as mediocre business managers.

The notion of "stasis" invites research into how technologies threaten a system's self-reinforcing rules, cultures, and institutions in late stages of system evolution. Stasis is obviously related to Hughes' notion of LTSs, and by focusing on late stages of a system's "evolution," it suggests how technologies threaten self-reinforcing rules, cultures, and institutions (so-called meso- or regime-level characteristics within the Multi-Level Perspective in sustainability transition studies). The concept of stasis also shares similarities with Hughes' "reverse salient" (a critical problem that needs to be overcome) because both refer to inhibitions to a system's "progress." An early appreciation of the multi-dimensional nature of stasis within traditional hardware may drive policy makers to examine and implement technical and social innovations along different axes of measurement that can also be viewed as conservative, thus effecting positive change without altering macro- (or meso-) level institutions. For example, instead of developing technologies that illustrate greater thermal efficiencies and lower-cost-per-unit of capacity, perhaps assessment standards such as declining waste emissions would gain popularity as the social, political, and economic environments changed. In the multi-level perspective framework, such changes represent macro-level (landscape) alterations of broad contextual considerations, though such changes may not be necessary [See 3.1.]

3.4.4. Future research

In our current age of global challenges, it is imperative to study energy LTSs in relation to development, socioecological inequality, and sustainability across the global North-South divide. LTS studies in the previous millennium tended to privilege Global North contexts; later LTS studies situated in the global South—especially on urban infrastructure and socioecological inequality—found LTSs there to be as varied, co-existing, socially discriminating, and context-dependent as those in the North. Such research, however, tends to reproduce the geographically bounded study of LTSs and its socioecological implications and ignores transcontinental LTS connections and other "sustainability telecouplings" [155]. Future LTS research should study how, for example, transcontinental coal, oil, or biofuel supply systems are implicated in the mutual shaping of (un)sustainability dynamics at diverse localities across the North-South divide [See also 3.3 and 4.5] [156].

Finally, the concept of technological stasis accords with the present appreciation for the role of hardware in sociotechnical system reconfiguration [157] relevant to a broad range of energy systems beyond thermal generating stations. One can interpret the growth of renewable energy systems as attempts to deal with stasis in traditional electricity generation hardware. Wind and solar technologies advanced rapidly in part due to increased efficiencies in the manufacturing process along with the increased scale size of components. But even currently attractive technologies may experience stasis, and energy planners need to be aware of the possibility. In the wind-turbine business, one can perhaps see hardware limits emerging in the manufacturing and transporting of large turbine components [158] alongside a limit imposed by politicians and others who assail the widespread deployment of the increasingly large machines, which have meanings of modernity and progress to many but which also emphasize the urban–rural divide [159–160].

3.5. Actors, networks, and heterogeneous systems

Actor-network theory and the study of heterogeneous systems emerged as an important area of STS research, and they have received growing interest in energy social science research. One of the significant contributions of these approaches has been the challenge to traditional dualisms such as actors and systems.

3.5.1. Actor-network theory

Actor-network theory frameworks argue that actors, networks, and systems should be regarded as co-constructed and relational concepts:

they manifest in relation to one another [161]. Three larger terms are essential for this conceptual interest:

- *Actors:* actors refer to all entities that make a difference in relation to the actions of others [162]. For example, in electricity provision, the actors that produce effects or even initiate actions range from legislation to economic theories, lifestyles, computer programs, wires, heat, fuels, and electron streams [163].
- *Networks and assemblages*: the reliable provision of energy comprises a *network* or an *assemblage* that integrates the actors at any instant [164]. These assemblages are continuously achieved by coordination and efforts among human and non-human actors.
- *Systems*: while dynamic, some assemblages display degrees of *systemness* [165] and hence durability and stability [166]. LTSs, for example, can be regarded as special cases of actors, networks, and heterogeneous systems that have become embedded because of their maturity, central design, or central control [167]. [See 3.4.]

3.5.2. The sociology and anthropology of infrastructure

Another useful toolbox to examine similar themes arises from studies of infrastructure, including computing and communications networks [168–169]. This work regards infrastructures as open and reconfigurable, geographically-distributed assemblages and directly complements recent STS work in energy [170]. Infrastructures, by definition, bring together heterogeneous systems – such as electricity, transportation, and heating systems in emerging integrated energy infrastructures, but also people, institutions, and practices, ranging from design to use and ongoing maintenance [171]. The anthropology of electricity and infrastructure emerged as a novel way to theorize politics, time, and promises in contemporary times, and it applies these insights to re-examine electricity and varieties of infrastructures [172–173]. This scholarship approaches infrastructures ethnographically and holistically, linking them with ways of life, sociality, power, politics, and expert knowledge such as computer models. It applies to everyday life and experiences, but it is also equally important for exploring the production of energy infrastructures [170].

These developments in STS, infrastructure studies, and anthropology render the entities in energy provision more open and unpredictable for analytical purposes. They offer resources in the form of reflexive discussions of methodology in energy social science research, sociotechnical transitions, and STS [174–175]. Single case studies and the strategy of following the actors have been utilized in STS for years but are now met with important questions about research designs, appropriate methods, and generalization of research findings, especially in complex interconnected technologies such as infrastructures. These challenges are pertinent to survey research but are increasingly addressed also in qualitative methodologies, such as ethnography [176–178].

3.5.3. Future directions

Three further research areas pose important future problems and consequently ways to advance the dual focus on heterogeneous infrastructural networks and actors, on the one hand, and methodological development, on the other. First, actor-network perspectives played an essential role in reformulating public engagement research [179–180], which has been recently applied to the co-production of energy citizenship and energy transitions in various sites including mobility, local electricity production, and residential energy use [90,181]. Second, the social study of energy markets is advancing and has started to develop more empirical and complex views on how economic actors are produced and integrated to energy infrastructures [182–185]. The distributional effects of energy markets for different kinds of actor – such as fuel-poor households – would demand specific attention [186]. [See 3.3.] The third area relates to how STS perspectives will apply to a heterogeneity of cases in different societies, states, democracies, and markets in various parts of the world [187]. For instance, examining the renewable energy sectors and markets in China requires that the core STS concepts and methodologies are developed to address the specific infrastructural assemblages where energy transitions are enacted in these settings [188–189].

4. The relevance of policy

Policy arose from our co-creation exercise as our second core category of influential sociotechnical perspectives, with specific topics centered on transformative innovation, sustainability experiments, governing complex transitions, the politics of design, and global disparities and hegemony.

4.1. Transformative innovation policy

There is a growing recognition that new forms of innovation must be harnessed and coupled to climate objectives [190–191]. Focusing on information and communication technologies (ICT), artificial intelligence (AI), the internet of things (IOT), nanotechnologies, biotechnologies, and robotics rather than on “traditional” energy or climate technologies brings to light the importance of innovation and radical breakthroughs. As such, innovation and sociotechnical change can be channeled to intensify mitigation via “deliberate acceleration” and “coalition building.” Within this body of work, three particular sociotechnical approaches hold promise: constructive technology assessment (CTA), responsible research and innovation, and transformative innovation policy (TIP).

4.1.1. Constructive technology assessment

Innovation has often been examined via CTA, which emerged during the 1980s as an alternative to Technology Assessment. The latter was developed in the 1960s to inform government decision making regarding technological change in order to reduce the cost of trial-and-error learning by anticipating the impact of new technologies [192–193]. CTA takes this claim further and proposes to engage users and civil society actors in an interactive way at the early stages of technology development, taking a co-evolutionary perspective in which the properties of technologies are not given beforehand but emerge as the result of interactive processes between business, governments, civil society, and users [194]. CTA has been used to evaluate and shape the use of energy technologies, such as research on the conditions of acceptance of new energy projects and on evaluating technologies at the local level such as low-energy housing [195–196].

4.1.2. Responsible research and innovation (RRI)

Inspired by CTA, science communication, ELSA (ethical, legal, and social aspects), and the philosophy of technology, among others, RRI emerged in the mid-2000s as way to address the growing tension between innovation as the driver of economic growth and innovation as a source of responsible solutions to basic needs [197]. RRI can be understood as an umbrella term, which has at least three main meanings: [198] (i) as a “figuration” that opens-up the politics of research and innovation to new relations between science and society;[199] (ii) as a specific approach that includes the dimensions of anticipation, reflexivity, participation and responsiveness;[200] and (iii) as a set of policies defined by the European Commission (gender equality, open access, science education, public engagement and ethics) [201]. While closely related to CTA, RRI has a broader scope: it is not only about understanding specific technologies in society but also about reshaping the whole research and innovation process, even before applications are considered. RRI has often been associated with emergent technologies such as nanotechnology and synthetic biology, but there are some examples on energy [202–203].

4.1.3. Transformative change

TIP is the latest of these approaches, and it focuses on

Table 3
Three frames, features and rationales for innovation policy.

Framing	Key features	Policy rationale
Innovation for growth	Science and technology for growth, promoting production and consumption.	Responding to market failure: public good character of innovation necessitates state action.
National systems of innovation	Importance of knowledge systems in development and uptake of innovations.	Responding to system failure: maintaining competitiveness, coordinating system actors.
Transformative change	Alignment of social and environmental challenges with innovation objectives.	Responding to transformation failure: pathways, coordination domains, experimentation and learning.

Source: [190–191].

transformation as an alternative "frame 3" to two other approaches to innovation policy: research and development (frame 1) and the national system of innovation and entrepreneurship (frame 2) (Table 3) [204]. The TIP approach shares some of its core elements with RRI and CTA: a focus on experimentation and reflexivity [205–206], directionality [207], co-production [208], and deep learning [209–210]. [See Sections 4.2 and 5.3.] In comparison with CTA and RRI, TIP takes a whole sociotechnical system approach to innovation policy, which starts from the needs of sustainability, environmental protection, equity, and democracy to propose a new frame for STI policy. It takes a whole sociotechnical systems approach to innovation policy, starting from ongoing developments in society that can be, through research and development, scaled to the systems level. [See Section 3.1.] TIP argues that change processes often start at the niche level and that public policy can foster the conditions for its development through experiments at the project, program, or policy level [206].

4.1.4. Future directions

Innovation policy is essential to the creation of alternatives to respond to the climate crisis. Government-funded research and development has played a central role in the development and global expansion of renewables [211], and it can play a central role in further developing alternatives to mitigate climate change. Research and innovation policy still holds the potential to promote further transformations; however, to do so we need profound changes in the policy practices that sustain it. Future work on TIP will continue promoting innovation policy as a democratic, experimental, and bottom-up process of directionality exploration. In particular, future research should explore how different TIP experiments evolve in distinctive contexts and sociotechnical systems, understand the politics and governance of the different contexts in which TIP is being implemented, and further advance in the development of tools and indicators that can guide this process. These issues will be addressed through a series of experiments to be implemented by research funding organizations associated in the TIP consortium [212].

4.2. Sustainability experiments in sociotechnical change

Experimentation plays an important role in research, policy, and practice related to the sociotechnical change and sustainability [213]. Experimentation is commonly seen as a means to explore, test, and develop new ways of doing things: ideas, concepts and theories, products and services, practices, processes [Section 4.2] business models, or policy interventions and modes of engagement [5.3]. It is often linked to earlier stages of innovation, where many uncertainties prevail. As opposed to formal methods in controlled environments in the natural sciences and positivist traditions, experimentation in social and sociotechnical contexts takes on a much broader and open flavor. It is oriented towards learning, discovery, and trial-and-error processes [214], as well as recognizing the overflows that are typical of sociotechnical matters and that resist neat confinement to laboratories and other controlled settings [215].

4.2.1. Variety of sociotechnical experiments

Accordingly, sociotechnical experiments tend to be practice-based, open, and oriented towards achieving transformational outcomes; i.e., they consist of "something that is tested in a metaphorical 'laboratory' where a group of diverse social actors team up to test something new in a dynamic real-life social context with the eventual aim to achieve a societal transformation." [216] Sociotechnical experimentation encompasses a wide range of activities, including field trials and demonstrations (on technical and non-technical aspects) [217–218], "living labs," and urban experiments [219–220], grassroots experimental initiatives and projects [221], and governance experimentation [222–223].

4.2.2. Variety of motives for experimenting

Sociotechnical experimentation involves the tentative exploration of novel ways of doing things, but it also requires dedicated learning processes as well as ways of accumulating knowledge and experience towards the development of novel sociotechnical systems and practices. Consequently, sociotechnical experiments should be conceptualized not as isolated but rather as inscribed in cumulative, collective, and multidimensional processes of experimentation and wider innovation processes. Accordingly, individual experiments may fulfil one or more functions related to sociotechnical dimension: these include testing technical feasibility, market trialing, showcasing and awareness raising, enabling behavioral change, exploring social acceptance, stretching institutional boundaries, or enrolling new actors and forming alliances [217,224]. Nonetheless, it should also be recognized that experimentation is inherently performative and value-laden: it produces social realities and ensuing forms of political ordering which can me more or less inclusive (e.g. legitimation, access, evaluation) [225].

4.2.3. Transformation-oriented experimentation

Real-world experimentation is attracting renewed interest, particularly in the contexts of climate governance [226], transformative innovation policy [190,227], sociotechnical niche development [228–229], and other purposive attempts to generate greater momentum and sharper directionality around path-breaking innovation efforts. In such contexts, experimental approaches are advocated as ways to overcome key rigidities related to innovation in different settings, namely a tendency for risk-aversion and incrementalism that result in overly bounded search processes. Individual projects or initiatives (less often a string of projects) are common vehicles for experimentation, particularly if oriented towards learning and discovery [230] and if evaluated in ways that maximize the open-ended exploration of new paths [231]. Projects benefit from dedicated funding, exceptional regulatory and institutional exemptions or loopholes, and significantly committed actors.

4.2.4. Strategic niche management

However, a recurring challenge concerns the "fragmentation of initiatives, and their tendency to remain isolated or short-lived, which ultimately reduces their potential for lasting and wide-ranging change." [232] Here, the notion of Strategic Niche Management (SNM) is useful, as it enables the connection of discrete and isolated projects (the "material sites" of exploratory innovation) to more collective and cumulative processes, and it problematizes relevant mechanisms. SNM suggests that radical innovations emerge in "niches," i.e., "protected spaces" in which radical novelty can develop in relative isolation from mainstream environments and selection pressures due to various forms of shielding, nurturing, and empowering [233]. The approach underscores the importance of three key developmental mechanisms occurring in cumulative sequences of projects (seen as the material sites): knowledge accumulation and circulation, the articulation of shared visions and expectations, and the building of networks and alliances of committed actors.

4.2.5. Future directions

Experimentation raises important problems at the intersection of science, policy, and practice, and increasingly so as it becomes framed as a "legitimate" way of intervening in the sociotechnical world to address societal challenges. Experimentation invites both caution and reflexivity, and it highlights open-ended research questions such as the following: What pathways for the wider embedding of experimental outcomes can be envisioned? (How) can experiments lead to transformative change? (How) can purposive experimentation be governed and evaluated? What are the unintended effects produced by experimentation? How can the performativity, promises, and expectations surrounding sociotechnical experimentation be critically examined? Lastly, given inherent breadth and interpretive flexibility, interdisciplinary conceptual efforts are needed to draw out the core features of experimentation and to ensure social ordering that more systematically interrogates experimentation in practice.

4.3. Governing complex transitions

Over the last two centuries, carbon-based energy systems and their global supply chains became sufficiently entwined with the functioning of the world's industrial economies that they acquired special attention from governments. Today, state-owned oil companies and publicly owned electric utilities or cooperatives still account for approximately half of the world's energy supplies [234], while much of the rest is extensively regulated (for example, via the monopoly provision of electricity, publicly constructed and managed electricity markets, or government ownership and permitting of mineral rights). Therefore, it is not surprising that the proposed transformation of energy systems to renewable alternatives is as much a question of *governance* as anything else. Governance therefore deserves special attention in future social science scholarship on energy transitions, especially where it intersects with work in STS, which is particularly attuned to the co-production of technological systems and the corresponding social and political arrangements that inhabit, organize, and govern them [235]. Three areas of research opportunity are illustrative.

4.3.1. Governing processes

STS needs to significantly upgrade the field's capacity to theorize the governance of sociotechnical systems change, both to account for the complexity of energy transitions and to apply the resulting knowledge to improve the ability of societies to successfully navigate their manifold potential pitfalls and enhance their outcomes. Energy systems entail highly complex sociotechnical entanglements among the energy sector, societies, and the environment, and changing energy systems will require wholesale renegotiation and reconfiguration of these entanglements around new ideas, technologies, politics, and markets [236]. In turn, the reverberations of these shifts will flow outwards into every corner of the globe, create ripples and rivulets of change that upend peoples' livelihoods, disrupt local economies and the communities dependent on them, create widespread and deep conflicts, transform electoral and international politics, and threaten to become torrential floods of social unrest and/or sociotechnical systems failures that overwhelm governance institutions [237]. STS research thus has the opportunity not only to examine how such transformations occur in complex socio-technological systems and the processes through which societies attempt to govern them, whether centralized or distributed, formal or informal, but also to contribute new insights into how the governance of transitions can be improved [238]. [See 3.3 and 5.3.]

4.3.2. Governing outcomes

Energy STS and social science research need to significantly deepen knowledge of what energy transitions mean for the full spectrum of stakeholders engaged in energy production, governance, and consumption. Evidence for the significance of these dynamics grows daily in the world's newspapers and social media. Declarations by cities, states, utilities, and even oil companies are proliferating around the need to create carbon–neutral futures, yet except for the smallest and simplest cases, the question of how to achieve these transitions—and to what ends—remains uncertain and, in many cases, hotly disputed [239]. Disagreements exist over the very possibility of creating carbon–neutral energy technology systems that can deliver current levels of energy supply, on every scale from cities to countries to the globe, as well as what it will mean to accomplish just transitions. To assess these questions requires extensive research into *the outcomes* of complex transformations of social-technological systems and especially the distribution, meaning, and imagination of those outcomes across diverse individuals, groups, and societies [240]. This research will entail building new capabilities to enable long-term observation, tracking, and analysis of the social and environmental implications of energy transitions, as well as new kinds of tools and frameworks for modeling and anticipating the future outcomes of transitions across diverse societies. Past energy systems have created some of the most unequal, corrupt, destructive, and unjust outcomes of any industry [241]. Reproducing those outcomes—or making them worse—would be a disaster. A just transition will therefore require the ability to look beyond simple cases, such as coal mining, to understand just how deeply energy transformation will penetrate into economies and societies, how the patterns of that penetration will disrupt existing forms of income and labor, and how new approaches to ownership in the energy sector might help to remediate global inequalities [242]. [See 3.3, 4.5]

4.3.3. Governing futures

Finally, energy STS and social science research needs to create and widely deploy innovative new approaches to envisioning and imagining the kinds of societies that will be built around carbon–neutral energy systems [243]. [See also 3.3, 5.3.] The scale and depth of transformation required to solve climate change, and the depth of integration of energy and society, means that human societies have a once-in-a-lifetime opportunity to reinvent themselves through energy innovation [244]. Solar energy, in particular, exudes interpretive flexibility [245–246]. Photovoltaics are a remarkably flexible technology, in terms of both the ability to incorporate them into diverse technical arrangements and the ability to link those arrangements to diverse forms and patterns of social and economic investment and ownership. At the same time, it will be enormously difficult to replicate petrocultures and oil economies in photovoltaics, and it is likely that other major facets of contemporary human societies, such as the kinds of cities we organize, may shift notably as well.

4.3.4. Future research

Across all three domains, STS and the energy social sciences offer a powerful foundation of a half-century of knowledge, methods, and approaches related both to energy and other sociotechnical systems, their risks, their ethics, their governance, and their futures. With that foundation, STS is positioned to ask critical questions about both the processes and practices of energy transitions, as they are occurring in diverse communities and societies, and the possibilities for how those processes and practices can be improved. The latter, especially, will require a major rethink of STS as a field of inquiry. It will not be sufficient to sit on the sidelines of the coming global energy transition and offer commentary. STS and the energy social sciences are positioned to productively and proactively engage, in a participatory yet critical fashion, in the co-production of new kinds of energy arrangements, the new kinds of knowledge that inform them, and the new kinds of societies that will get built around them [98,247–248]. What kinds of cultures and markets will get designed, instead? What are the design options? What are their potential societal and ethical dimensions and implications? Who gets to be involved in imagining, deliberating, designing, and implementing sustainable energy futures?

4.4. Politics of design and resilience

STS scholars have advanced the theory of technological politics to critically examine political consequences of a broad range of technologies across contexts [249]. In response to the growing influence of technoscientific experts and the rapid institutionalization of technical knowledge in governance systems, STS scholars have debunked the idea that expertise is beyond political analysis [250–251]. This argument is grounded on the influence of scientific knowledge and experts on political decision-making process [252]. Two streams of research are apt in this regard: comparative politics of technology, and risk and resilience.

4.4.1. Comparative politics of technology

One common direction in research on technological politics focuses on comparative studies of how technological politics varies between developed and less developed societies for energy infrastructures. [See also 4.5.] An example is nuclear power. Arguably, no other source of energy is more controversial than nuclear power [253], and this form of energy production has been marked by heated debates around the world [254–256]. Despite a short-lived “renaissance” that it enjoyed at the beginning of 2000s, the reputation of nuclear energy was severely damaged after a series of meltdowns occurred at Fukushima Daiichi nuclear power station in Japan following the earthquake and tsunami on 11 March 2011 [257–260]. Even before Fukushima, nuclear politics was an important subject within STS. For example, Hecht uncovered in French nuclear politics the interplay between bureaucratic politics and nuclear expertise, resulting in what she termed a technopolitical regime. In the other Euro-American contexts, scholars have found different patterns of state politics that shaped the institutional structure of nuclear energy [261–262]. In the developing world, nuclear energy appeared to be a very promising option despite massive opposition from grassroots groups [263]. Even after Fukushima, nuclear politics remains strong especially in certain Asian countries. For instance, China shows strong commitment to advancing its nuclear energy production [264]. Likewise, despite on a smaller scale, India has broadened the possibilities for nuclear energy development [265].

4.4.2. Risk and resilience

In the post-911 world, studies of technological systems underwent a shift from risk to resilience [266]. In the wake of Fukushima, the value of resilience has become increasingly important in technological politics, particularly for research on energy infrastructures [267]. As more uncertainties are emerging in energy sectors due to the sociopolitical dynamics and environmental changes around the world, resilience was put in the spotlight due to a belief that it is a panacea for the problem of increasing frequency of disaster and fluctuating financial markets [268]. Although some scholars appear suspicious of resilience as a neoliberal project no different from previously popular slogans such as “green” and “sustainability,” [269] resilience has received serious attention from transnational institutions, governmental agencies, business corporations, scholars, and policy-makers across the globe. Within the area of energy politics, the concept of resilience is relevant when it is framed as a hybrid entity. The notion of “sociotechnical resilience” embodies this aspect of hybridity [270]. Drawing on insights from STS scholarship, the concept implies that resilient capacity lies in the intersection between the technical configuration and social structure of systems. Both aspects play equal roles in determining whether energy infrastructures are able to withstand unexpected crisis and recover in short time.

4.4.3. Future research

First, more research is needed to unpack particular forms of power relations in the non-Western context in which technology became the center of socioeconomic transformations [271–272]. Moreover, future work should better connect how technological politics is also manifested in the materiality or design of technology. Research can explore how technological politics shapes devices, objects, and infrastructures on which modern society is increasingly dependent in everyday life [273]. One promising avenue could be political studies of energy infrastructures, which involve the ways in which energy systems are materially configured and how the configurations matter a great deal in the political economy of energy production and consumption [155,274]. Moreover, currently few studies have applied sociotechnical resilience as a framework to examine urban disaster resilience [275]. The use of this framework can be extended to other sectors of infrastructures especially those situated in megacities across emerging economies. Two research areas are potential to explore. One deals with the impact of urban digitalization on city resilience, an ongoing phenomenon rapidly unfolding in cities from Jakarta, Mumbai, to Seoul and Beijing. The other looks into the ever-expanding network of energy infrastructures that cut across regions. This is a global scale of analysis that aims to examine system vulnerabilities lurking within in the intersection of social and technical configurations.

4.5. Global disparities and hegemony

This section focuses on the construction of and challenges to hegemonic views of energy (See Fig. 6). This section understands hegemony in two ways: the global asymmetry of countries based on power, resources, and wealth; and the view of nature as merely a resource to be used by humans [276]. Thus, this section provides a comparative and global perspective on the problem of inequality and power in sociotechnical systems study. [See 3.3, 4.1, and 4.4].

4.5.1. Asymmetry and marginalization

To organize the discussion, two axes are used to characterize the different perspectives (see Fig. 7). The global disparity asymmetry axis refers to the relationship between mainstream discourses, policies, actors, regions, and institutions and their peripheral counterparts. Thus, there are works in which scholars clearly recognize and analyze inequalities, but other research ignores or at least marginalizes the global

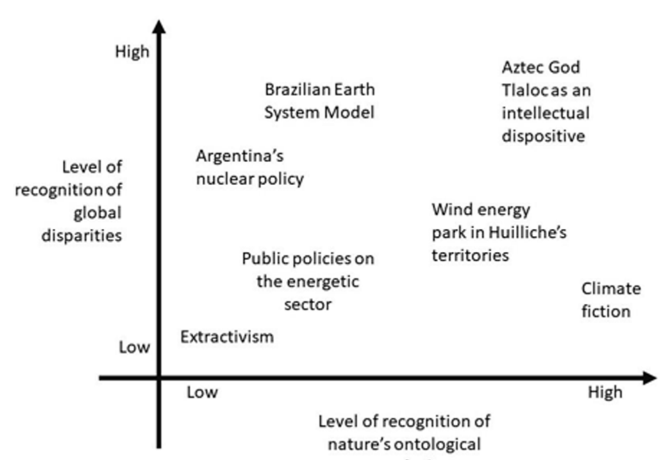


Fig. 7. Social scientific works by level of disparities and of nature's ontological complexity. Source: Authors.

disparity of power. The second axis refers to the extent to which studies recognize ontological questions in relation to the nature and consequently the production, circulation, and consumption of energy. At one end of the axis, nature is viewed as commodified, and its ontological status is reduced to a resource. At the other end, multiple ontologies describe a state of affairs in which nature is experienced as a multiple entity [277] or even as a living thing, and in some cases fictional accounts are used [278].

4.5.2. Hegemony in a world of low ontological complexity

In the lower left quadrant, research on policies related to energy [279–281] and on extractivism [282] view nature in instrumental terms and accept that the world is unevenly distributed in terms of access to natural resources, energy production, and energy consumption. Approaches within this quadrant can include studies of international regulations, foreign investment, resource extraction, and the effects of neoliberal policies. In the upper left quadrant are studies that are more concerned with disparities but retain an ontological framework in which nature is basically a source of resources and an object of inquiry. For example, some studies focus on policies of nuclear development or infrastructures in peripheral countries and how the countries faced pressures from Northern powers [283–285]. This research can also focus on infrastructure and knowledge that counterbalance the data produced by Northern institutions. For example, Hochsprung-Miguel et al. [286] describe how Brazil decided to become the first Southern country to produce climate models in order to improve understanding of the climate in South America. With the acquisition of a new supercomputer and investments in climate science, the Brazilian Earth System Model was recognized and included in the IPCC's modeling [287].

4.5.3. Hegemony in a world of high ontological complexity

In the lower right quadrant are studies where the ontological complexity of nature is more prominent. For example, Tironi and Sannazzaro [288] highlight the ontological differences with respect to nature when analyzing the involvement of Mapuche people in a wind-energy project in the Huilliches territories in Chile. As they point out, this participatory experiment attempted to show that another energy was possible, "a Huilliche energy: a competitive project framed within the requirements of a capitalist economy that make Huilliche communities a protagonist of the process" [288]. Another example of the awareness of the complexity of nature's ontology, also in the right-bottom quadrant, refers to climate fiction because, as Jensen [289] shows, it is possible to learn from the interplay between "real" nature and "fictitious" nature by anticipating real and fictitious consequences of actions and policies that might shape imaginaries [See also 5.5].

Finally, in the upper-right quadrant, studies focus on the epistemological incommensurability of intellectual knowledge products that, because of power relations, were downgraded. This approach recognizes not only global power disparities but also the ontological complexity of nature. For example, in a study of the Spanish Conquest of America, Arellano [290–291] examines how Tláloc, taken by the Spanish as the God of the Water, is depicted as human, animal, and artifact at the same time and is actually an inscription much like contemporary scientific graphs and models of climate. Arellano's groundbreaking research shows that Tláloc expresses climate-meteorological knowledge produced in the interplay between the atmosphere and pre-Columbian collectives; in other words, it is an atmospheric deity that portrays simultaneously climate phenomena and Mexican culture.

4.5.4. Future directions

This schematization of the varieties of ways of thinking about the complexity of nature together with North-South power disparities also provides a way of conceptualizing future agendas. More research on the causes and consequences of extractivism in peripheral regions needs to be done, recognizing that this problem mirrors those raised by dependency scholars back in the 1950s and 1960s. Social and anthropological investigations of the worldviews of non-Western people that challenge the Western understanding of nature as resource promise to be innovative but hard to combine with policy-oriented research on energy. Likewise, recognizing global disparities in research on the asymmetrical resources of different regions to produce knowledge on energy and climate should be widened by paying more attention to the diverse actors involved in the process of knowledge production [See 3.3, 5.1]. Succinctly, it could be said that those works produced under the assumption of high global disparities and nature's ontological complexities should focus on how public policies can be implemented. Meanwhile, the challenge for policy analyses is, following STS lessons, to make the landscape of knowledge production, circulation and use more ontologically and politically multifarious. [See also 3.5.]

5. The importance of expertise and publics

This section covers five topics of sociotechnical perspectives from our co-creation exercise on energy dealing with the category of expertise and publics: public engagement and deliberation; expertise and climate science and policy; expertise and democracy; expectations and visions; and imaginaries, storylines, and frames.

5.1. Public engagement and deliberation

There is a dynamic STS literature on participatory democratic practice [292–296]. STS scholars are deeply invested in developing conceptual frameworks that theorize and experiment with public engagement on energy and society issues. This work covers everything from wind energy and solar siting [297–298] to natural gas fracking [299–300] and smart grid scenarios involving energy customers [301]. The later engages with an emerging interest in how individuals are materially participating in a world that is becoming ever more object-driven and device-oriented [90].

5.1.1. Downstream and upstream engagement

Energy and environmental decision-making is often characterized by state-driven "notice and comment" engagement processes, such as open houses, public hearings and comment periods, which limit public engagement to box-checking exercises [302]. In these cases, public engagement is driven toward the end goal of "educating" the public and acquiring social acceptance or a social license to operate for a particular project. There is a desperate need for new modalities of public engagement that bring greater transparency, accountability, and humility into the staid politics of project planning [303–305]. As Jasanoff has argued, debates about public participation and expertise often degenerate into "purely instrumental comparisons of alternative procedural formats for bringing publics into technical decisions" [306]. She advocates for advancing public participation by refocusing on the rights, obligations, and cognitive capacities of citizens to guide science and technology toward shared visions of societal betterment [307]. [See also 5.3.]

In contrast to downstream project approval, STS scholars have argued for models of "upstream" engagement where publics can impact research priorities and technological design criteria in the interest of building "more socially responsive, just and equitable forms of science and technology." [308] Yet, as Stirling cautions, even well-intentioned STS "upstream" processes can still produce a disciplining participatory discourse that can "close down" rather than "open up" avenues for deliberation [309].

5.1.2. Changing the dynamics of engagement

The above reflections on why and when inform the issue of *how* we engage. Chilvers and Kearnes claim that most STS interventions remain in the interpretive vein and have tended to "shy away from the necessary work of intervening and reflexively engaging with systems, institutions, and practices of participation." [310] In their 2005 book, *Science and Citizens,* Leach et al. describe the more "performative and embedded" ideas of scientific citizenship that recognize knowledge as "inalienably cultural in that it embodies, reflects and projects commitments of a human kind." [311] Similarly, stories can become gathered data objects that reveal much about what and how people understand and communicate energy issues [312]. Instead of focusing on unitary policy recommendations, these kinds of exercises can pose alternative questions, focus on neglected issues, and include marginalized perspectives. As Lezaun et al. have written, by curating novel forms of participation, scholars can elicit accounts of public issues that would otherwise remain under-articulated [313].

5.1.3. Future research

In the future, energy-focused public engagement scholarship will likely expand beyond site-and-issue-specific work toward broader notions of energy democracy. As mentioned above, STS scholars have largely focused on public engagement in terms of siting conflicts and highly structured citizen engagement fora and summits. In the energy context, this scholarship often ends up engaging, deploying, or challenging concepts related to decide and defend (DAD), NIMBY (not in my backyard), or more recently PIMBY (please in my backyard) approaches to project development [160]. As Ryghaug et al. have discussed, there has been a lack of focus in STS energy studies on everyday life and the material realities of energy transitions [90]. The decision to engage or disengage in the sphere of one's own home represents a very different scale of politics, which is at once more intimate, personal, and emotional than public facing actions may be. Chilvers and Pallett discuss "energy democracies" as an alternative framing of public engagement work that encompasses the mundane aspects of sociotechnical transitions [308]. The challenge for STS scholars is how to make this new strand of work speak to policy action and structural change, perhaps through the mode of developing "social laboratories" of energy democracy. Chilvers and Pallett argue that these laboratories have the potential to "to tackle issues of equity, inclusion, institutional responsiveness, and social change with regards to participation in whole energy systems." [308]

5.2. Expertise, climate science and policy

The social construction perspective seeks to interrogate the underlying assumptions of scientific knowledge and the translation of science into public policy and everyday practices. With respect to climate science, attention has focused less on the traditional problem of STS—how climate science is made, with some notable exceptions, mostly mentioned below [127,314–316] —and more on how climate science is constructed in the media and in governments.

5.2.1. The construction of climate knowledge

STS research on climate change had, for a long time, an overriding focus on the credibility of climate knowledge and – relatedly – an emphasis on understanding what kind of construction climate knowledge was [316–318]. At least three central aspects have been repeatedly highlighted in social studies of the challenges of the interface of climate science and policy:

- First, there was the point that the IPCC – a novel form of international scientific actor – was essentially engaged in climate-knowledge assessment [319–320]. The IPCC has no labs or research ships of its own but is involved in research synthesis, putting together findings and ideas from diverse fields. It is also an intergovernmental body, meaning that national representatives (be they scientists or not) are involved in responding to and shaping the principal texts. This is a distinctive form of knowledge-making, and the IPCC has not itself been subject to much detailed study (though see exceptions such as the study of the West Antarctic ice sheet) [321]. This additionally raised the question of how the people with the "right" expertise were selected for IPCC roles and how the various forms of expertise were combined in IPCC deliberations.
- Second, there was the point that several key aspects of climate science deal with modelled knowledge and with scenarios for the future [315,322]. This was important, in part, because it provided a rich seam for those who wanted to throw doubt on mainstream findings; however, it was also exploited by those who wanted more urgent climate action and were critical of what they saw as benign assumptions (such as the tendency to bank on a capacity for "negative emissions.") [323]
- Third, the communication of scientific conclusions and, on top of that, communicating the idea that there is special kind of warrant for scientific analyses (based on peer review and other forms of quality assessment) was a central preoccupation of the IPCC and other actors [324–325]. This emphasis had the ironical consequence of setting the predominant science-policy discourse around climate science at odds with the broader tendency towards greater public participation in knowledge making [326–328]. The IPCC has been concerned with global representativeness – ensuring that scientists associated with the Global South are not omitted from leading positions – but public engagement has been highlighted chiefly in relation to possible policy responses and strategies for climate-change adaptation.

5.2.2. Climate denialism and competing problem constructions

From the perspective of 2020, the context for arguments about construction has moved on in the sense that, though deniers of climate change are still active in several countries, the main political and policy arguments are no longer about the reality of climate change but about ways of responding to moves away from carbon-intensive fuels and practices. Denialists have moved ground to making sure that affirmations of climate change are not woven into other policy areas, in US trade negotiations for example. It is notable that when the US decided to pull out of the Paris climate agreement, the public justification was given in economic and scientific terms, aiming to stress the negative effects of the accord on the US economy and how little difference the US's non-participation would make in total greenhouse emissions were it to withdraw [329].

The key "constructionist" issue is now much more at the level of different institutional actors, in competing social worlds, constructing the leading issues differently, using different frames (see Section 5.5). For example, there is the well-documented point that oil companies are still prospecting for new fields and starting to exploit fresh deposits even while the great majority of countries have pledged or are setting short-term decarbonisation targets. As yet, this clash of worlds is not reflected in fuel companies' share prices [330]. Even within policy communities committed to decarbonisation, there are competing visions: for example, between an emphasis on substituting current approaches (swapping electric or fuel-cell cars for diesels) and a demand for sociotechnical transformations [331].

More broadly even than this, there is the issue of the way in which the whole discourse is shaped. Of late, decarbonisation has tended to eclipse sustainable development as the overall policy framing; however, it is evident that ideas related to the circular economy are now being promoted by governments, industry bodies, and some research funders. Key here are the ways in which these rival constructions may conflict. For example, a recent UK projection from the Committee on Climate Change (the government's official independent climate advice body) anticipated electric vehicles displacing current road transport as part of UK decarbonisation. However, rival calculations from a materials and earth science background suggested that this ambition would place an insupportable demand on minerals needed for the batteries: just the UK vehicle fleet's batteries would consume the global cobalt production [332]. Since most vehicles are only used for a fraction of the day on average, having the cobalt sitting unused most of the time could be seen as a misuse of cobalt stocks, an unnecessary exploitation of the mineral wealth of the Democratic Republic of Congo, and of the energy needed to extra the metal in the first place.

5.2.3. Future research

There is a need for a more broadly sociological examination of current discourses discussed in the previous section. One additional example is the idea of a "climate emergency," which relates the current climate-change problem to war-time levels of urgency. If people are not panicking – so the suggestion goes – then they haven't understood how bad the problem is (this idea is also closely allied with the successful school "climate strikes" campaign which helped to constitute today's youth as a group with a distinctive interest in the climate issue). On the other side, many policy makers (especially those of an economics bent) suggest that panic is exactly to be avoided. Policy options adopted in haste are often ineffective or wasteful, and may result in perverse outcomes (as with the idea that Europe's flight from carbon led polluting industrial manufacture to relocate to East and South-East Asia, where it may well have provoked more CO_2 emissions per ton of output than the original plant would have caused) [333]. Furthermore, there is an interesting party politics and international politics around the willingness to declare a climate emergency. In many countries, declaring a condition of emergency has particular implications in terms of freedom of action by the executive or liberation from specific financial constraints, as has been amply demonstrated in trillion-dollar responses to the COVID-19 crisis. But analysis of the reasons for climate-energy declarations suggests that such pronouncements may be made for more mundane or tendentious political motivations. Over thirty years ago sociologists became fascinated with the "risk society"; we now have novel characterizations in the making.

5.3. Expertise and democracy

"Sociotechnical research" into dynamics of political change around climate and energy challenges has paid surprisingly scant attention to issues of democracy [334]. Important insights and possibilities emerge in new work challenging through material practice entangled in "hybrid assemblages," overdrawn divides between "expertise" and "democracy" [See also 3.2 and 5.2] [335–337].. But with few exceptions, [338–344] the study of possible mechanisms for "energy transitions" and "climate transformations" tends to focus more on relatively narrow *technical* policymaking, than on explicitly *political* questions concerning the changing of cultures in which policies are enacted. [345]

5.3.1. Cockpitism

Much "sociotechnical" research is driven by "cockpitism" [346] – treating political change as a matter for a singular expert controlling agency. This involves relatively little questioning of fundamental political drivers of climate and wider "sustainability" challenges. Unacceptable erosions of human well-being, social equality, and ecological integrity highlighted in the United Nations' sustainable development goals tend to be addressed as marginal "externalities," residual "institutional failures," and challenges to "optimize" "policy mixes" – rather than as deeper transformations in entrenched interests, concentrated power, centralized authority, elite privilege, and related flows of appropriation.

This growing technocratic style of sociotechnical research on energy and climate transformations contrasts with central roles still played by ideas and values of democracy in much practical activism [347–350]. And it is striking when academic attention in the research fields turns from building *understandings* of the supposed dynamics of transformation, to *documenting* the emerging movements themselves that deeper themes grow more prominent, for instance, around "energy democracy." [351–356] [See also 3.3, 5.5.] It seems the relevance of democratic struggle to ambitious progressive change is generally more obvious to activists than academics, for whom "research impact" disproportionately comes in service to "policymakers." [357–359]

5.3.2. Transdisciplinary action research

To be fair, much academic attention is still given in this field to essential roles for transdisciplinary "action research." [360–364] But even in many ostensibly progressive forms, 'inclusive engagement' tends often to be enacted in instrumental and symbolic ways [365–370]. Subject to over-arching expert "framing," [371]"evaluation," [372] and criteria of "excellence," [373] this caters more to "invited" than "uninvited" engagement [374]. Such processes differ from democracy in being more about "*choosing how to do it*" than "*deciding what to do*" [375–376]. The core interests of "sociotechnical research" itself tend to remain more fixed on elite processes of "knowledge brokering," [377] "visionary leadership," [378–379] and "transformational leadership," [380] than on open, uninvited forms of participation. Even themes around energy and climate "justice" often addressed more in terms of ethical principles and legal instruments, than imperatives for bottom-up, direct emancipatory action [381].

5.3.3. Future research

Albeit not without exceptions, there are grounds for concern that sociotechnical research of many kinds bearing on energy and climate transformations is getting the emphasis wrong. And the stakes are potentially high. For a core message is clear from histories of progressive mobilizations – for instance against slavery, colonialism, racism and oppression of serfs, workers and women [345]. Despite diversities of contexts and interpretations, it is difficult not to recognize the central roles played by democratic struggle of many kinds, in the furthering of these progressive ends [334]. If sociotechnical research is to play as crucial a part as is possible and needed in current pressing global challenges, then it should perhaps spend less time on hubristic servicing of expert policy dashboards for imaginary global cockpits? A more humble but effective role arguably lies in scholarship and analysis as collective actions in their own right – helping to seed, catalyze, and nurture the wider unruly complexities of democratic struggle that are so essential to progressive transformation [382–383].

5.4. Expectations and visions

Expectations, defined as representations about the future, truly matter in sociotechnical change. A range of studies has explored the way expectations not only represent but also propel research fields and innovation trajectories [384]. The common lesson is that expectations are more than claims about the future that eventually will be false or true; more importantly, they also shape what is going on in the present [385]. Expectations typically are connected and appear as building blocks for bigger narratives.

5.4.1. Visions and anticipation

When the building blocks appear jointly in a regular and predictable way, they may aggregate into a "vision" or *Leitbilder*, which can be defined as a more-or-less coherent package of expectations, in a recognized narrative [386]. Visions overlap with other kinds of symbolic forms associated with technology and technological change. [See 5.5.] Expectations are forceful due to their circulation amongst engineers, firms, and government, which operate in a "sea of expectations." [387] When expectations are readily available, they can justify particular research directions, coordination efforts, and research agendas. This condition leads to particular dynamics, such as the pressure to fulfil the promise once it is widely accepted, or the promise-requirement cycle [388]. So-called "enactors" are committed to a particular technological promise, while "selectors" need to choose between competing options; they exchange and assess expectations in "arenas of expectations" such as conference or trade journals [389].

5.4.2. Entrenchment

In the case of energy innovations, expectations circulate differently than, for example, consumer products, because sociotechnical change in energy infrastructures is less volatile, has more sunk investments, and brings together public and private interests [390–391]. Apart from path-dependency, the entrenchment of energy options leads to more elaborate expectations that connect firm strategy, regional policies, and technological futures [392–393]. A second characteristic of the energy domain is its strong connections to imaginings of modernity [394–395]. For instance, the global expansion of private automobile use, fueled by oil, has been accompanied by persisting ideas of freedom, prosperity and autonomy [396]. Likewise, new forms of mobility such as the 'hyperloop' rejuvenate the awe for speed and the mastery of distances [397].

5.4.3. Future research

In general, studies of expectations point to a tragic condition. Although imaginations of the future undeniably allow novel directions in the first place, they easily also become straightjackets. Promising technologies typically lead to global races amongst firms and governments, and to prisoner's dilemmas, with metaphors of not missing boats, or trains that cannot be stopped. Imagination is typically hailed as a gateway to freedom and self-determination, yet in sociotechnical change with its inherent strategic games, it readily leads to a sad decrease of choice. Therefore, it is important to better study how to avoid becoming a tragic prisoner of imaginations of the future. A second direction for future research is to investigate the locality of opportunities and choices. Novel directions in energy typically appear as global solutions, leading again to global races at the expense of local ownership. An example of how to address this challenge of locality is the recent work of Levanda [398] and colleagues, who studied the viability of regional sociotechnical imaginaries. [See 5.5] This direction also resonates with Bruno Latour's latest plea for taking the materiality and locality serious in order to address the climate crisis [399].

5.5. Imaginaries, storylines, and frames

Sociotechnical perspectives that use the concepts of imaginaries, storylines, and frames are part of a broader family of approaches to sociotechnical analysis that focus on the analysis of meaning and the semiotic dimensions of both sociotechnical systems and their governance. Other, related approaches in the literatures on energy and sociotechnical systems include cultural styles [400], cultural expectations [401], fantasies [402], and habitus [403]. [See 5.4.]

5.5.1. Imaginaries

A leading example of the analysis of sociotechnical systems from the perspective of cultural meanings is research on sociotechnical imaginaries, understood in this context as "collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific and/or technological projects" [404]. Research can focus on the visions of future benefit that national governments and industrial actors deploy to legitimate policies that support technological change and even transitions, and one approach is to develop comparative analyses of national government imaginaries [405]. Researchers have also recognized that imaginaries rarely go uncontested, and various studies have examined the alternative imaginaries of counter-hegemonic actors such as social movements, civil society organizations, and new entrants in industries [406,406–407,407–408,408–409,409–410,410,437–438]. In episodes of political contestation over policies that guide technological change and development, there can be multiple imaginaries at play, and they can be connected with different actors and interest groups [411]. When the analysis of imaginaries becomes linked to actors and political conflict and coalitions, it begins to overlap with the analysis of storylines and frames.

5.5.2. Storylines and frames

To the extent that the study of imaginaries recognizes contestations over competing imagined futures, it approximates another approach to the cultural dimensions of sociotechnical systems: the study storylines in discourse coalitions [412] and the study of collective action frames [413–414]. A storyline is a "condensed statement summarizing complex narratives," [415] and this work draws attention to the discursive dimensions of policy-making, including energy and climate policy. However, unlike analyses that remained focused only on the rhetorical or symbolic dimensions of politics, the study of storylines draws attention to their role in coalitions and the changes in storylines in response to competing storylines and political conflicts. Thus, this approach, like that of frame analysis, connects the study of meaning to actors and strategy.

A collective action frame is a scheme of interpretation used in collective action and mobilization [416]. This approach to the symbolic dimensions of politics has been used heavily in social movement studies, but the concept of strategic action framing has diffused widely and is also used more broadly in the study of institutionalized political conflict. An important dimension of framing analysis is the study of counter-framing and the flexible way in which frames can be used to enhance and strengthen coalitions in energy politics [417]. As coalitions grow and develop, frames also undergo changes to accommodate the views of new constituents and supporters. Moreover, frames that work at the local level may not work as well at higher levels of spatial scale. In energy politics, one example of the expansion of frames as large coalitions are formed is the use of "energy democracy" to provide a banner to unite the disparate goals of coalitions that might otherwise remain disconnected by their more focused attention on green technology, environmental justice, or green jobs [418]. Thus, a framing perspective approaches the issue of "energy democracy" from a cultural perspective by asking how different groups find the concept of "democracy" to work well as a broad banner under which disparate grievances can be organized.

In comparison with the study of imaginaries, the study of storylines and frames tends to be more focused on specific policy arenas and competing coalitions, does not necessarily involve symbolic constructions of sociotechnical futures, and can involve subnational spatial scales. These approaches also contrast with prominent policy process theories, such as advocacy coalition theory, which tends to emphasize the stability of core beliefs and coalitions [419–420].

5.5.3. Future research

One of the important areas to address in future research is a comparative perspective on how imaginaries, storylines, and frames can be deployed with the greatest effectiveness to accelerate socially desired transitions (e.g., to low-carbon energy) and likewise to decelerate undesired technologies (e.g., continued fossil-fuel use). [See 3.1.] Thus, this perspective can contribute to the analysis of the conditions under which successful transition policies can be developed, approved, and implemented, but without making the assumption that language and symbolism alone can provide solutions. As indicated above, these studies can involve showing how the frames change when new groups in the energy politics space come together to form broader coalitions to gain greater political effectiveness or as they shift scale from dispersed local mobilizations to broader national and international policy arenas. Moreover, attention to framing and coalitions can potentially help to identify successful strategies in situations where there is opposition to transition policy, such as approaches to energy transition coalitions that can overcome some types of opposition from political conservatives [421].

Another important area is to examine how the analysis of imaginaries, storylines, and frames can be used to address the tensions between expertise and publics. Current work has increasingly drawn attention to contested imaginaries, competing storylines, and counterframing and to how the different symbolic constructions are connected with coalitions and competing interest groups. However, these methods could also be extended to examine anti-science and anti-energy-transition framing associated with right-wing populism and religious conservatism. Although these perspectives are widely used in studies of media frames, there is also a place for bringing a more sociotechnical perspective to the topic that might examine how the frames become connected with different proposals for the design of energy-related sociotechnical systems.

6. Discussion: Looking inward, outward, and across the frameworks

The 15 sociotechnical perspectives resulting from our co-creation exercise reveal a wide variety of conceptual frameworks and topics of research. In this section, we provide a synthetic analysis in two sections: the theoretical, methodological, and topical choices that are implied in the wide range of topics and frameworks that are covered, and the connections among future directions that the authors identify as important next steps. We frame these discussion sections as an "inward and outward" approach (6.1) and an "across" approach (6.2). Although this section draws from the co-created sections above, it also taps into the ten-year systematic review of STS articles on energy and climate. This section draws both from our co-creation exercise (the expert judgment of our co-creators) as well as unused but novel data from our earlier systematic review, with details offered in [16].

6.1. Theoretical, methodological, and topical choices: looking inward and outward

One way of thinking about the wide range of sociotechnical perspectives is the set of choices that a researcher must make when integrating a sociotechnical or STS perspective into the research project. We identify three central choices: (1) theoretical framework and (2) method, or "looking inward" at assumptions, and (3) topic, which involves "looking outward" at energy-related problems with attention to social inequality and geographical diversity.

A previous review of broad theoretical choices in technology studies used the long-standing tripartite distinction of agency, structure, and meaning (also known as the three "I's" of interests, institutions, and ideas), and it added normative perspectives [161] (See Fig. 8). This approach also works well as a way of classifying theoretical choices for researchers who adopt sociotechnical perspectives in the study of energy. Of the frameworks discussed here, agency tends to be highlighted in research on practices, the system builders of LTSs, actor-networks, transition experiments, engagement, and democracy (Sections 3.2, 3.4, 3.5, 4.1, 4.2, 5.1, and 5.3). Structural approaches are prominent in frameworks that emphasize inequality and mechanisms for addressing power differentials in governance (Sections 3.3, 4.4, 4.5, and 5.3). (Indeed, we will return more to this theme or tension between agency and structure in the next sub-section). Meaning-focused approaches are especially prominent in research on the construction of climate science and the analysis of visions, imaginaries, frames, and storylines (Sections 5.2, 5.4 and 5.5). Although social science research is generally explanatory and descriptive, it can often have philosophical implications for a critical and normative project that examines the connections between energy and societal transformation (Sections 3.3, 4.1, and 5.3). Many of the approaches combine some or all of the four elements, and some highlight the combination, such as the Multi-Level Perspective, LTS research, and transformative innovation policy (Sections 3.1, 3.4, 4.1). Thus, one of the issues to consider for future research directions is how the different sociotechnical perspectives can be brought together in ways that integrate attention to agency, structure, and meaning and that examine the deeper normative and critical implications of the problems and solutions.

A second group of choices involves the underlying research design and methods utilized to analyze data, present findings, and generalize results. STS research is historically qualitative, and portions of it (historical and ethnographic research) tend to be idiographic. However, work influenced by sociology, political science, social psychology, and other social sciences also brings to STS a nomothetic orientation, that is, a goal of producing middle-range theoretical generalizations. Comparative analysis is generally presumed to enhance the generalizability of results, and mixed or multi-methods design can improve triangulation, rigor, and validity [422].

However, methodology remains an area where future research involving STS and sociotechnical perspectives as applied to energy could show greater attention. For example, in the companion article with the dataset of publications at the nexus of STS and energy social science, less than a third of the studies used comparative analysis or mixed methods [16] (See Fig. 9). More troublingly, greater than one-third of articles (35.3%) had no research design or no methods section at all. This implies the field would profit from more closely considering methodological issues rather than always discussing epistemology and theory. This lack of attention to methods is problematic in terms of enabling generalization and replication, explaining the parameters by which data were collected and analyzed, and acknowledging limitations. Thus, the literature would benefit from more attention to generalizability and the methods that enable it. More promisingly, almost one-third of articles had some sort of novel integrative conceptual framework that sought to integrate or theoretically triangulate concepts—with Appendix I showing the details. This use of multiple frameworks sharpens the utility (and future potential) for studies to look

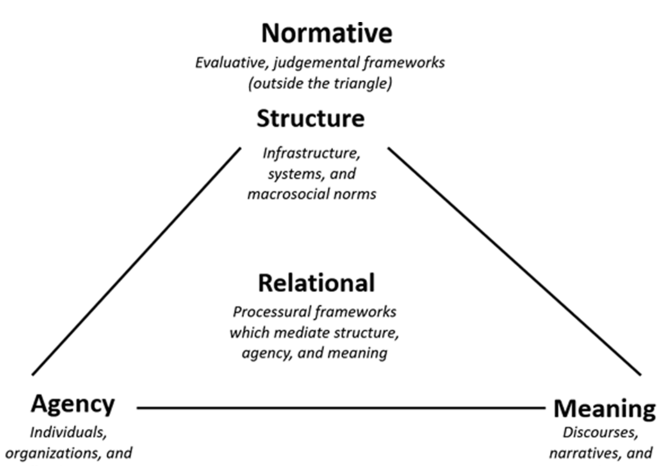


Fig. 8. A typology of theories by agency, structure, meaning, relations and normativity. Source: Authors, modified from [161].

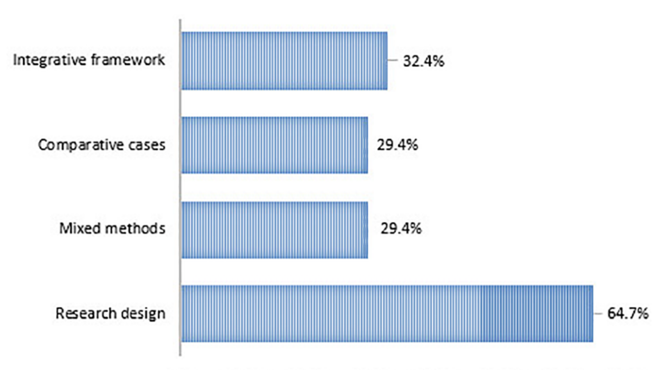


Fig. 9. Stated frameworks, case studies, methods and research designs in STS scholarship from 2009 to mid-2019 (n = 68). Source: Authors, based on coding of [16].

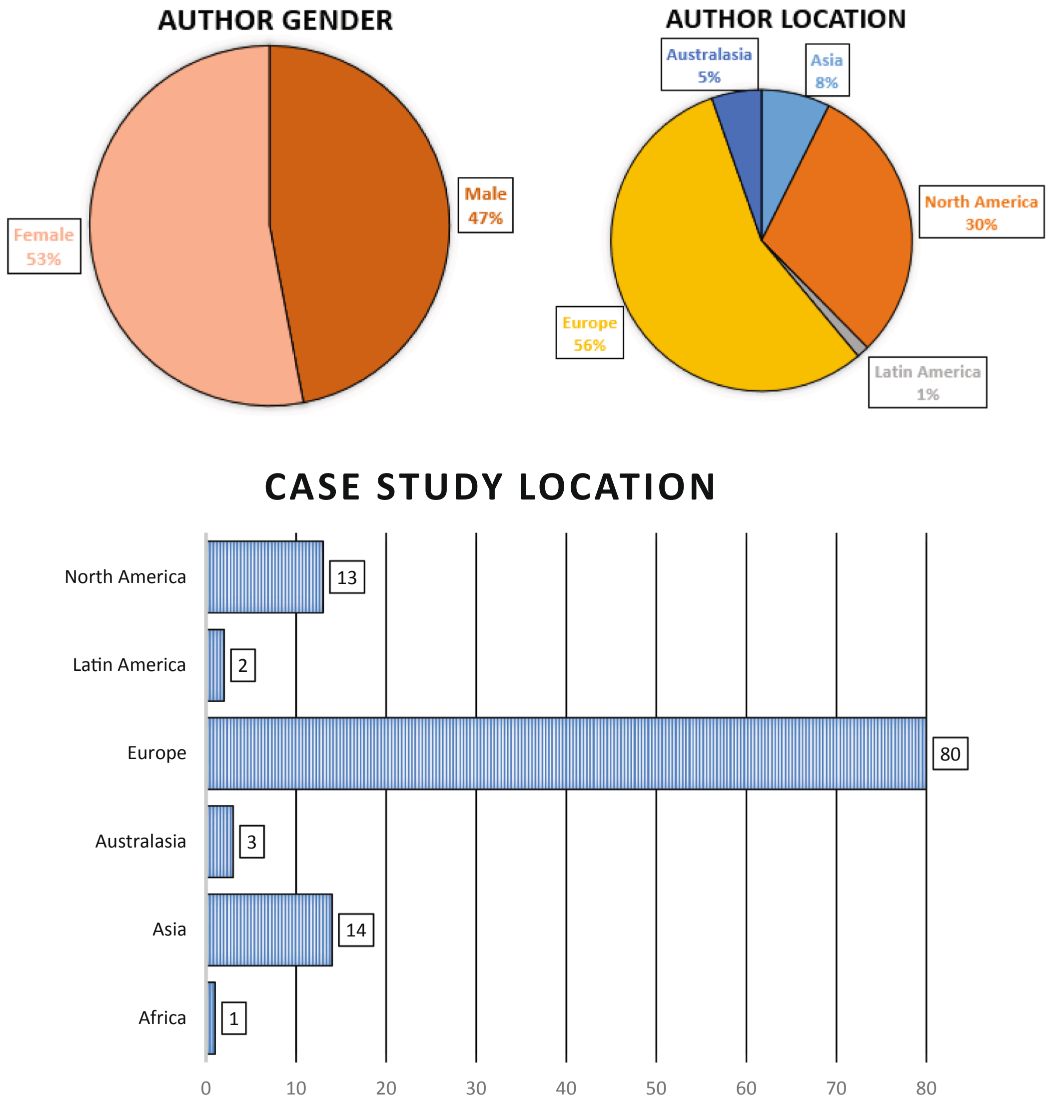


Fig. 10. Gender, Location, and Case Study focus of STS articles from 2009 to mid-2019 (n = 68). Source: Authors, based on coding of [16].

at similar cases or problems through the lens of various perspectives, then compare them and assess relative strengths and weaknesses.

A third major choice involves the topic of the study within the broad spectrum of energy-related research problems. Several of the sections of this article pointed to the need for greater attention to various types of diversity in future research. This goal for future research is not surprising because calls for attention to diversity can also be found in STS and in sustainability transitions studies. Examples of how the authors in this article conceptualized diversity include the diversity of users and actors in studies of practices and heterogeneous networks (Sections 3.2, 3.5); racial, ethnic, and gender differences and inequality (Section 3.3); and sites of research located outside the developed, industrialized, and Western countries (Sections 3.4, 3.5, 4.1, and 4.5).

Again, the concern with diversity is not just a perception of the authors in this study; the lack of diversity can be found in the broader fields of energy research and STS. On this point, a content analysis of 15 years of energy scholarship and 4,444 articles identified only 15.7% of the authors as female [423]. However, in the smaller and more specific data set of 68 articles in the companion review of STS and energy social science, we found that 53% of the authors were female (or 79 women out of 149 authors). This finding is promising; however, the topic of the studies rarely included gender or issues related to women. (See Fig. 10).

With respect to geographical diversity, in the same companion dataset, Europe, Australia and New Zealand, and North America accounted for 91% of author institutions. (To ensure sampling diversity, the review included STS journals from Latin America and East Asia, but few articles in the journals met the inclusion criteria of research on energy, a significant engagement with STS concepts, a novel perspective on the literature, and use of empirical material to support the theoretical argument.) After we removed four cases that looked at regional institutions (e.g., the European Union or regional governance) and six that focused only on a global technology (e.g., wind or solar energy), there were 113 distinct geographic sites analyzed. Of these studies, 82% examined sites in Europe or North America, and across all of the studies, 90% looked at developed economies. There was only one African case, Senegal; only two in Latin America, Brazil and Chile; and zero in the Middle East. Of the fourteen Asian cases, these were on China, Indonesia, Japan, Philippines, South Korea, Taiwan, and Thailand—with most of them about Japan. There was not a single study on India or any of the countries on the Indian sub-continent, no small island developing states in the Pacific, and none of Russia or any of the Central Asian republics. There was only *one* study on China, despite the fact that that it is the world's second largest energy economy and the largest emitter of greenhouse gases, and that study was limited to an assessment of the co-production of standards for vehicle-to-grid and electric vehicles.

Essentially, most research at the intersections of STS and energy social science remains, despite the fact that it tries so hard to be critical, WEIRD: focused on Western, Educated, Industrialized, Rich, and Democratic spaces [424–425]. It also remains largely focused on high technology such as smart grids, wind turbines, solar panels, and nuclear reactors rather than more mundane, and possibly useful and widespread, energy technologies such as light bulbs, cookstoves, or bicycles, despite the fact that Bijker's pioneering work studied two of these alongside bakelite, a plastic [12]. This critique of a WEIRD bias was levelled initially at American undergraduates who form the bulk of data sources in the experimental branches of psychology, cognitive science, and economics, as well as allied fields in the behavioral sciences, but it is apt in the context of sociotechnical perspectives and energy social science research as well. Unfortunately, WEIRD research samples from an overly thin slice of humanity, and yet researchers may assume their findings are universal. It focuses on industrialized societies, but no small-scale or agrarian societies where many of the world's poor reside; it focuses on Western cultures, but not the rich mosaic of non-Western cultures that shape the beliefs and lives of more than half the world's population. Finally, WEIRD research often oversamples "typical" populations—white, middle-class, middle-aged men or women, for example—but not "atypical" types such as the disabled, ethnic minorities, the poor, the old, or the young. This narrowness in populations may cause researchers to miss important dimensions of variation and to devote undue attention to analytical tendencies that are truly unusual in a global context.

6.2. Connections: Looking across the sociotechnical perspectives

Although this overview of sociotechnical perspectives revealed different choices for adopting sociotechnical perspectives in the study of energy, there were several connections in the areas that the authors and co-creators collectively identified as future directions based on their expert judgment, with every subsection connecting to at least one other subsection (see Table 4). Many subsections had multiple clusters or connections with other subsections. After making an inventory of the future directions described in the 15 sections, we grouped the connections into five main areas: the conditions of sociotechnical and societal change; the societal embedding of actors; justice, power, and democracy; imaginaries, visions, discourses and frames; and governance. The first one, conditions of change, does not show up as a distinct theme with a red circle because virtually *every* section and subsection engaged with it.

6.2.1. Conditions of sociotechnical and societal change

Understanding the conditions of the interaction of sociotechnical system change and broader societal change is central in this nexus of research because of the failure of many of the world's highest-emitting countries to develop an adequate policy response to global warming and because of the parallel crisis of growing inequality and authoritarianism. Change comes in many forms, with one known typology [426] articulating:

- Linear change, which occurs in systems with highly stable parameters and with a record of the past that enables us to detect and measure the future with extreme accuracy;
- Creodic change, similar to growth and development from a seed or a fetus, which occurs via a catalyst that causes rapid growth after a threshold is reached, making it difficult to perceive before the potential is realized;
- Epidemic change, based on the probability of an event that cannot be predicted with certainty, such as earthquake in × amount of years, and where probabilities change as time goes on and under the impact of human action;
- Dramatic change, like the plot of a play or a marriage, with interactions and social factors cannot be predetermined and "play out" as we indulge with them;
- Chaotic change, which is where irreducible randomness makes prediction impossible.

Geels and Schot draw from such theories of change and place them into the context of sociotechnical transitions in the top panel of Fig. 11. The bottom panel of Fig. 11 discusses organizational change as described by Van de Ven and Poole. It classifies four different models and mechanisms of organizational change, and how to manage it. Teleological change is planned, it sees change, often manifested through innovation or organizational strategy, driven by visions and goals that lead to implementation, followed by evaluation and perhaps modification. This change is often driven by heroic actors or collective deliberative bodies. Lifecycle change develops through successful phases or stages, usually driven by some sort of code, program, or governing logic. Evolutionary change occurs based on the combination of cycles of selection, variation, and retention, especially as organizations compete for scarce resources and adapt themselves for advantage. Dialectal change results from struggle between clashing groups or countervailing forces, where stability and change are best explained not by heroes, growth, or evolution, but instead an imbalance of power relations.

The conditions for change can include both endogenous sociotechnical system factors and broader societal, political, and institutional factors. For example, the sections on sustainability transitions research (3.1) and on transformative innovation policy (4.1) suggest that more attention is needed to understanding the processes that affect the acceleration of a transition and the societal embedding of innovations. This area of research would bring sociotechnical perspectives into conversation with research on institutional change, policy processes, and broader historical or landscape changes. Thus, future research requires work that continues to develop the convergence of sociotechnical perspectives, sustainability transition studies, policy studies, and sociological and historical perspectives on institutional and societal change. For example, the section on transformative innovation policy section (4.1) opens up innovation and system transition to the connections with broader societal change. Likewise, the section on power, gender, and justice (3.3) highlights the need for research on social innovation, and the sections on governance (4.3) and on expertise and democracy (5.3) point to the need for research on how energy transitions can be linked to broader societal transformations.

Part of the agenda of developing a better understanding of the conditions of energy transitions involves inquiry into their visions, frames, and assumptions. This area of inquiry includes the analysis of the strategic uses and value of the symbolic dimensions of transitions and their role in transition coalitions (Section 5.5) and the critical inspection of sometimes taken-for-granted framings and visions. For example, the section on expectations and visions (5.4) cautions that technological visions can become a prison that limits the imagination, and the section on expertise and social construction (5.2) likewise queries the underlying assumptions of the framing of climate-mitigation policy. Likewise, the frame of a "climate emergency" is apparently helpful from the perspective of motivating governments and organizations to action, but it has a potential downside associated with lack of democratic processes in political emergencies.

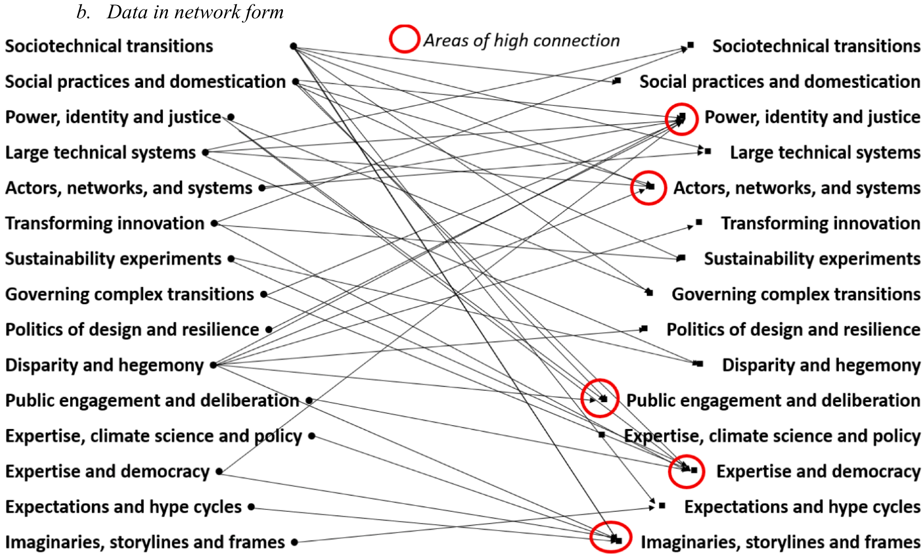
Several sections point to the need for future sociotechnical research that addresses the definition and scope of a system and systemic change. For example, the section on governance (4.3) discusses how definitions of carbon–neutral futures are highly contested with different views about effects and outcomes. The section on sustainability transitions (3.1) discusses the limits of research on single elements of a system and suggests the importance for research on whole systems. Likewise, broader systems are also central in the LTS literature (Section 3.4) and in research on the politics of design and technology (Section 4.4). The LTS literature points to the importance of social and political conflict and to the effects of spatial scale, and the politics of technology

Table 4
Connections or crossovers between subsections of energy and climate sociotechnical research (as noted in Sections 3, 4, and 5).

a. Data in tabular form

	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.3	5.4	5.5
3.1															
3.2	x														
3.3		x													
3.4	x		x												
3.5	x	x	x	x											
4.1	x														
4.2		x				x									
4.3	x		x												
4.4			x												
4.5			x	x	x	x			x						
5.1		x	x												
5.2															
5.3		x	x			x		x			x				
5.4	x														
5.5	x									x		x	x	x	

b. Data in network form



Source: Authors.

approach notes how technological systems such as nuclear energy become connected with systems of governance in a technopolitical regime. These approaches point to new research problems involving the politics of energy infrastructures and the definition of resilience as both a policy goal and system design goal (Section 4.4).

After policies have been approved and adopted, research is needed that examines how to improve implementation (Section 4.2). Concepts such as technological stasis and reverse salients from the LTS literature are relevant for this problem (Section 3.4), and the section on sociotechnical experimentation (4.2) outlines a series of research questions that include the governance of experiments and their links to broader social change. The transformative innovation policy approach (Section 4.1) also draws attention to the need for experimentation with democratic, bottom-up approaches to policy development and implementation.

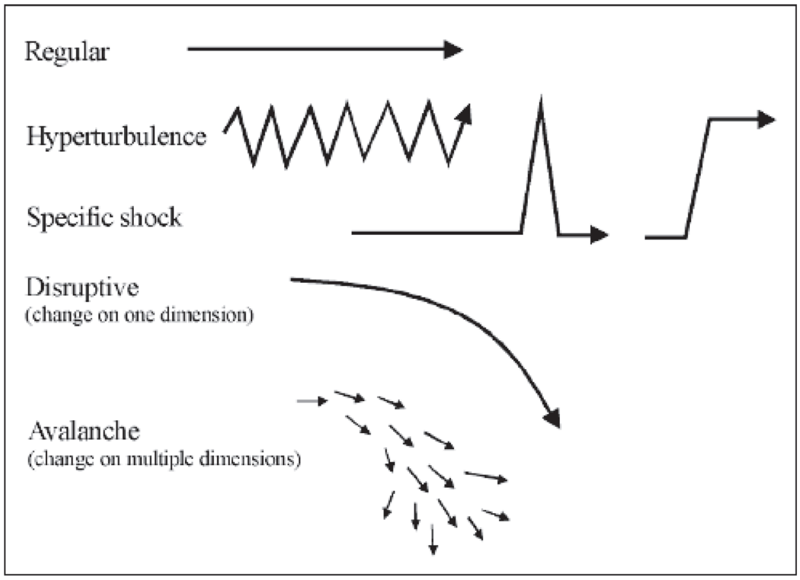
In summary, many of the sections point to the opportunity to bring sociotechnical perspectives into the study of the conditions for effective change (in policy, program implementation, and society), and in doing so they show how sociotechnical perspectives on energy can improve the analysis of how changes in energy systems are connected with broader societal change and conflicts.

6.2.2. The social or societal embedding of actors

A second cluster of connections centers on actors (and their networks and systems that shape their agency). This group envisions actors as fairly independent but also "socially embedded" [429] or "societally embedded." [41] The embeddedness of actors relates back to long-standing debates across the social sciences about the role of agents and agency versus structure (already discussed in Section 6.1), which Jessop [430] resolves a bit differently by showing both are reflexively and recursively organized when viewed by different academic vantage points (see top part Fig. 12). Building on the work of Broadbent, agency and structure can also exist across a spectrum or "periodic table" of material, social, and cultural dimensions shown in the bottom part of Fig. 12 [431].

The drivers and constraints on actors are a recurring theme within our sections, with work focusing on the societal embeddedness of sociotechnical transitions pathways (3.1), policy actors or communities of practice (3.2) and even "ecologies" of actors and their participatory networks (3.2, 4.3, 5.3), the "system builders" behind large technical systems (3.4), and of course actor-network theory approaches (3.5). Actors may also show up as innovation intermediaries (4.1, 4.2) or social movements (5.1, 5.2, 5.3).

a. *Top panel: Sociotechnical systems change*



a. Bottom panel: Organizational change

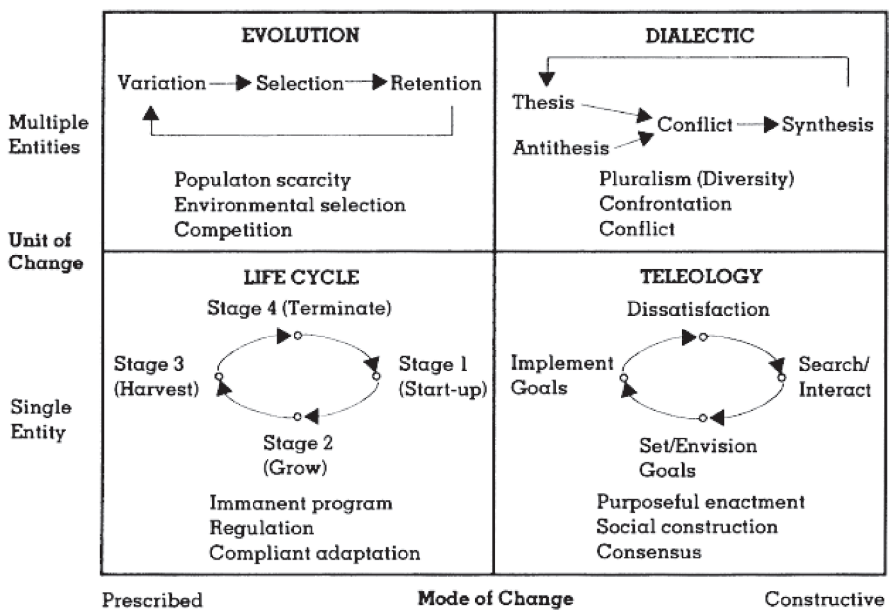


Fig. 11. Types of sociotechnical systems and organizational change management. Source: Top panel from [427] and bottom panel from [428].

6.2.3. Justice, power, identity and democracy

A third area of connections is future research that brings sociotechnical perspectives to research on justice, power, social identity, and democracy. The rise of right-wing populism in many countries, the failure of climate-mitigation policy at a global level, and the growth of climate-justice and energy-democracy movements have created fertile ground for researchers' increasing concern with inequality, power, and politics. This work connects sociotechnical perspectives on energy with parallel work on the growth logic of capitalism [432]. The section on power, gender, and justice (3.3) calls for more research in this tradition, such as studies of corporate influence and "the social dynamics of power imbalances." This approach could involve an expansion of the focus of innovation from technological to social innovation, an approach that has some overlap with the discussion of transformation innovation policy (Section 4.1) as well as proposals for LTS research to focus more on the haves versus have-nots (3.4).

Likewise, the section on the politics of design and resilience (4.4) explores a parallel set of issues and draws attention to economic inequality both within and between countries. Perspectives from the global South (Section 4.5) can lead to the critical questioning of assumptions about nature based on indigenous worldviews and to analyses of how peripheral countries attempt to overcome global asymmetries of scientific knowledge. Additionally, global policy agendas such as resilience can offer benefits to less developed countries while

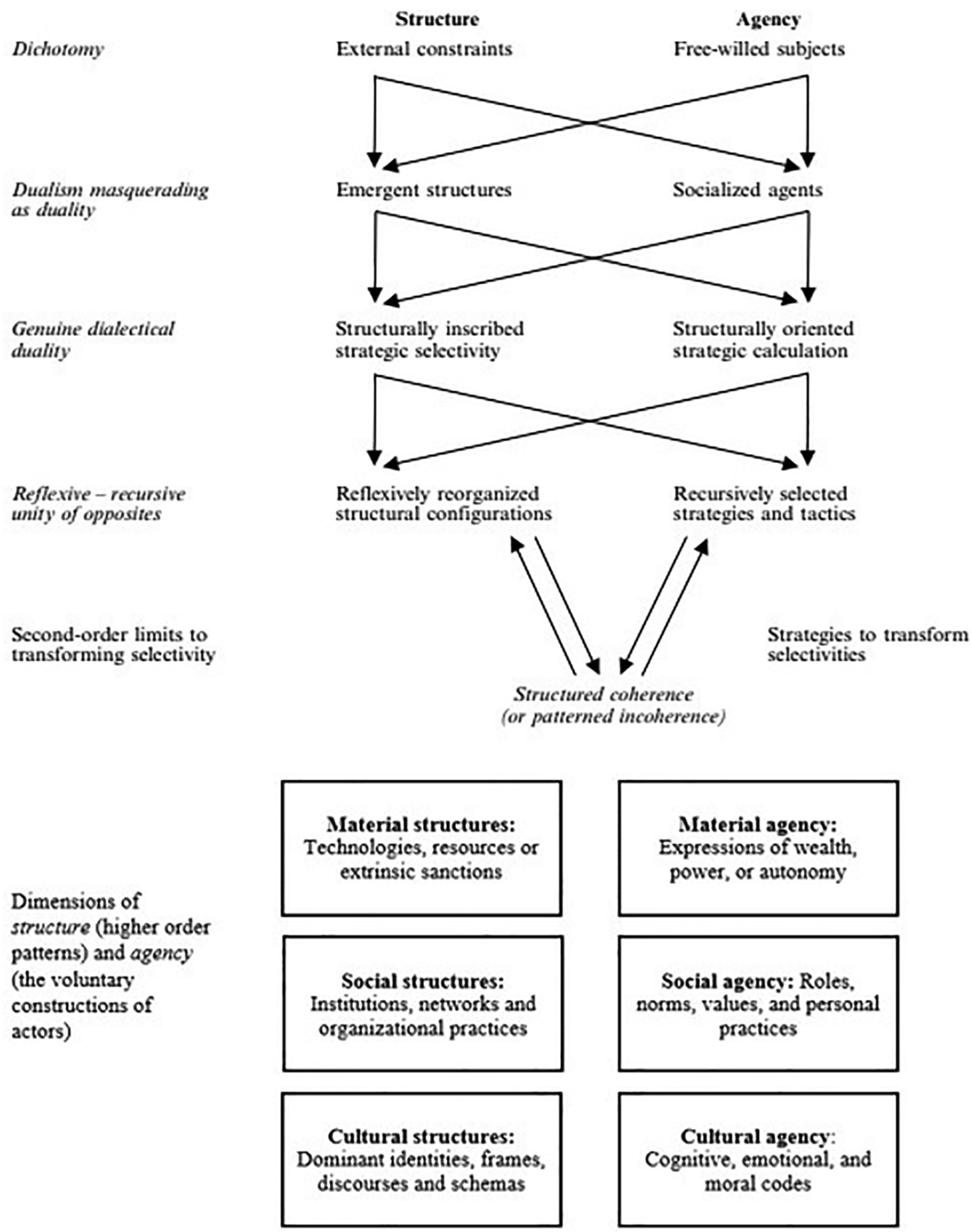


Fig. 12. The reflexive and recursive nature between structure and agency. Source: [430–431].

also molding those benefits in a neoliberal direction (Section 4.4), and the visions and imaginaries associated with globally diffused sociotechnical systems can limit the articulation of alternatives (Section 5.4). Together, these sections underscore the need for greater geographical diversity that values the standpoints of the perspectives of less developed countries and regions for developing critical analyses of the assumptions of sociotechnical research on energy.

The section on power, gender, and justice (3.3) and the section on expertise and democracy (5.3) also call for greater attention to the study of activism guided by democratic values, where new research themes can emerge, such as energy democracy. Both sections suggest the need for a fundamental shift of emphasis in sociotechnical research on energy, in which research helps "to seed, catalyze, and nurture the wider unruly complexities of democratic struggle that are so essential to progressive transformation" (5.3). Nevertheless, as the research field grapples with issues of mobilized publics, political activism, participatory processes and new forms of material practice, it will need to return to the complex problems associated with potential tensions between, on the one hand, democracy and public engagement, and, on the other hand, the need for science-based policy that provides a competent approach to policy problems, solutions, and implementation. Long recognized in studies of expertise and publics, associated tensions will require thoughtful analysis in the growing literatures in energy social science on social movements, energy democracy, and public engagement.

6.2.4. Imaginaries, visions, narratives and frames

A fourth area of significant clustering relates to how energy and climate technologies or issues are depicted in language, how they are connected with (and help co-construct) imaginaries, visions, narratives, discourses, and frames. At the core of these aspects of technology is an assessment of the symbolic aspects of communication that highlights the relationship between what passes for scientific knowledge or engineering capability, and the symbolic forms that are used to frame such understandings, such as stories, expectations, and visions [433–435]. Such symbolic forms imply that the boundary between technical, rhetorical, and policy issues is a porous one, and they show how actors become enrolled in particular storylines and plots [436–437].

Studying visions and related symbolic constructions reveals how humans communicate their thinking to others. They can:

- Manage expectations and create (or deconstruct) hype cycles surrounding new and emerging socio-technical systems (Section 3.1);
- Offer a heuristic device for revealing the specific problems that need to be resolved in order for climate science (5.2) or a low-carbon transition to be realized or established (3.4);
- Enable the identification of stable frames for target setting and monitoring progress (4.2);
- Specify metaphors and relevant symbols, narratives, or moralities that bind together different stakeholder groups (5.4, 5.5);
- Reflect varying perspectives on technology from a diverse group of stakeholders (3.3, 5.1, 5.3, 5.5)

Because the technological landscape is always changing, visions and related symbolic constructions can shape how we think about energy and therefore shape the energy future. Furthermore, and critically, deconstructing visions and discursive tactics can offer a diagnostic tool (learning from previous visions) and also reveal the vested and even hegemonic interests and power relations underlying them [438].

6.2.5. Governance and participation

The previous areas of future research topics imply the fifth: attention to governance and public participation. In other words, research on the conditions that facilitate systematic change has increasingly turned its attention to policies and politics that guide the changes; and research on justice, democracy, and power has likewise turned attention to how to improve the governance of energy. The section on governance (4.3) identifies research on outcomes based on the "long-term observation, tracking, and analysis of the social and environmental implications of energy transitions" as a central future direction. Likewise, other sections (3.3, 5.3) connect the analysis of governance to social movements and political reforms that would improve the democratic potential of energy governance.

Closely related to sociotechnical perspectives on governance is research on, and occasionally participation in, new forms of public engagement and participation. As the section on public engagement and deliberation (5.1) indicates, STS and other researchers have already developed a substantial literature that criticizes and intervenes in public engagement and participation processes. This section identifies a challenge for future research as "curating novel forms of participation," including forms that involve values associated with energy democracy. This perspective is similar to proposed future research in the section on expertise and democracy (5.3), which also suggests more attention to unruly forms of governance such as social movements and activism. Perspectives from actor-network theory (3.5) also provide new approaches to understanding the co-production of publics, experts, and engagement processes.

Other approaches to governance included experimentation and the role of users. The section on sustainability experiments (4.2) notes that sociotechnical experiments "encompass a wide range of activities," but some experiments involve grassroots participation and new forms of governance. Thus, future directions include connecting research on experimentation to governance and "transformative change." The section on social practices (3.2) also points to a shift in research topics from traditional understandings of users to research that reimagines the use of technology as "material participation" and a site for public engagement.

7. Conclusion: Towards plurality and parallax

This study identifies how energy social science research is benefiting from STS and related sociotechnical perspectives. These perspectives can bring a material and epistemic dimension into energy social science research, and they can be integrated with a wide range of social science frameworks. Doing so, we argue, can help the field be more systematic and open about "parallax"—the fact that objects appear to be different from contrasting angles and are more changeable from close-in than far-out. Stirling argues that greater attention to parallax can help resolve the limitations of single theoretical frameworks (See Fig. 13), converting hegemonic (integrative and standardizing) "eagle-eye" views into more conditional and pluralistic "worm-eye" views. [439]

We interpret parallax to mean the notion that a single object, technology, problem, or research project can be viewed across multiple lines of sight, or even that multiple objects can be viewed across multiple lines of sight. STS may already be known in some circles for generating greater parallax than some other fields and for being more critical and reflexive than most disciplines—a role that is valuable. The parallax problem for STS approaches may be less the question of whether it can internalize parallax in its individual studies (a navel gazing approach) than whether it can find ways to use STS's parallax orientation and the diversity of energy research across many STS studies, in aggregate, to help open up parallax benefits for the larger world of energy and climate research.

This plea for parallax also comes from within our results across Sections 3 (sociotechnical systems), 4 (Policy), and 5 (expertise and publics) in this paper. These sections repeatedly call for STS researchers to look across to the moderately familiar, i.e., less dogmatism within these silos of STS research and a push for the transitions people to engage more with the social construction people, or the gender people to talk to the power people, the actor network scholars to speak with the expectations people—and vice versa. To borrow from the literature, the community needs to embrace "another logic" with more "theoretical triangulation," [161] "multi-paradigm analysis," [441] "strong objectivity," [442] and ontological or intellectual "crossovers." [443–444]

That said, research that is focused on a single conceptual framework, even from a single discipline, is not necessarily a shortcoming, and many outstanding studies may contribute to or advance only one framework. Also, the claim that more diversity necessarily leads to productive research and legacy insufficiently acknowledges the risk that too much diversity may lead to a dispersed, fragmented field that does not accumulate knowledge let alone wisdom, leaves no lasting legacy and is not understandable or recognizable for external audiences [445]. It runs the risk of case studies of less value to broader society, too many different concepts or frameworks, and creating difficulties for aggregation or generalization.

However, theoretical pluralism has its advantages, for it "can help researchers select the most appropriate analytical tools for their research question, properly credit those who contributed towards the development of theory, and avoid dogmatic adherence to particular ideas that can stifle both conceptual advancement and communication between disciplines." [422] Zooming in, and zooming out, as a practice can culminate in more holistic research strategies that help offer more comprehensive and likely valid explanations and answers to proclaimed research questions. Moreover, multiple research styles that should debate and interact with each other, and the tensions between them, are necessary for a healthy, socially relevant field or discipline. These all help deconstruct or de-privilege any single theory, approach, or unit of analysis.

At its most general level, this study suggests the potential for the benefits of parallax by bringing, much more self-consciously,

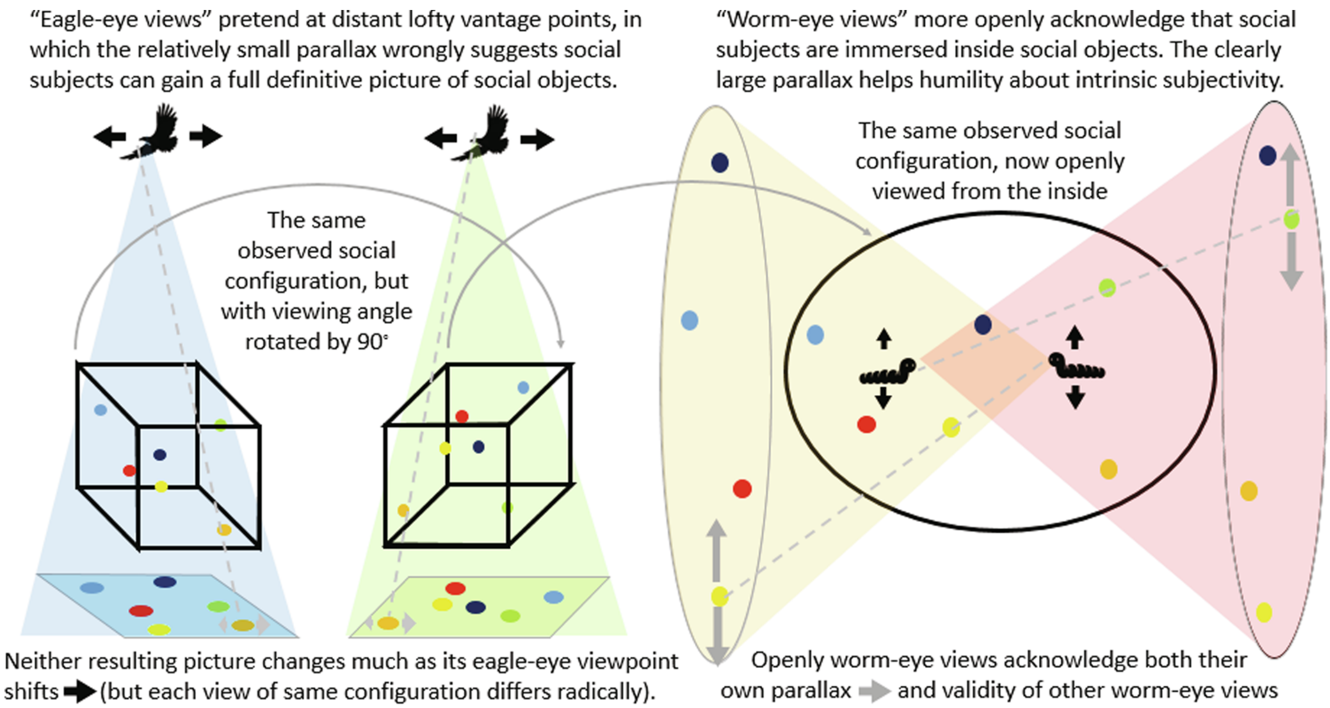


Fig. 13. Eagle eye views, worm eye views, and ontological parallax. Source: Authors modification of [440].

sociotechnical perspectives into conversation with the wide range of theoretical frameworks already evident in energy social science research, including frameworks drawn from policy studies and political science, sociology, psychology, and other disciplines. Often these other fields tend to view technology and questions of material design as a black box that is separate from the societal and behavioral processes that are the focus of attention. Similar to how the field of sustainability transitions research has drawn on sociotechnical perspectives from STS, there are opportunities for bringing these perspectives into conversation with a wider collection of frameworks in energy social science. Parallax has particular resonance for the context of energy and climate because transitions are periods when taken-for-granted assumptions about how energy systems work are being called into question, reconsidered, remade, etc., which is when you need to make sure that a broader array of voices are heard and perspectives considered.

Another benefit of acknowledging parallax involves the triangulation of perspectives across the different sociotechnical approaches. By breaking down sociotechnical perspectives into 15 different topics and by examining both the choices involved in research that involves sociotechnical perspectives and the connections that are emerging across the perspectives, we also suggest the benefit from an appreciation for parallax that comes from triangulation across sociotechnical perspectives. Although the approach of this study divides the perspectives into distinct categories, most of the researchers who contributed to this project are themselves at home in multiple research fields, and they actively work toward theoretical synthesis in their own research projects.

Furthermore, although itself a distinct sub-section in 5.3 on transdisciplinary action research, our results suggest that academics and STS researchers broaden outward by working with more diverse research topics and researchers. The community needs to pay far more attention to diversity in non-Western or non-Northern countries and contexts—with our recent data suggesting that 91% of authors applying STS concepts or approaches to energy and climate come from Europe, Australia and New Zealand, and North America; and 90% of case studies look only at developed or highly industrialized, Western countries.

The STS community needs to also reach beyond academic research as a whole to engage with other key stakeholders, ranging from

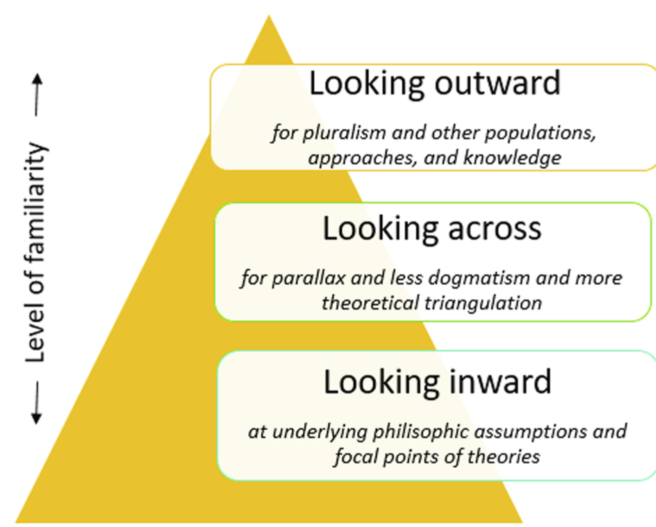


Fig. 14. A call for inclusive, reflexive, and diverse STS research. Source: Authors.

business firms and governmental organizations to user groups, trade unions, and marginalized populations. It must, as Fig. 14 suggests, look outward and across rather than only inward. This will help ensure that the rich knowledge base offered by STS does not remain idle but is taken up, used, and integrated with the practical knowledge of policymakers and other practitioners. To do this well, we may need larger team-based efforts that go well beyond any prominent individual, department, university, or program. An emphasis on transdisciplinary research also demands that reflective conceptual thinking not come at the cost of undermining the need for clear cut energy and climate action in the here and now—conceptual novelty needs balanced with practical and pragmatic utility.

The points of connection across the 15 perspectives—and our call for inclusion, reflexivity, and diversity—suggest that there is clear concern with future research that is relevant to the political and policy problems associated with both social inequality and environmental sustainability dimensions of energy social science research. Some of the sociotechnical perspectives call for research oriented especially to advocacy work involving energy justice and energy democracy, whereas others focus on research problems that can improve policymaking and program implementation. In both cases, these sociotechnical perspectives are distant from the traditional scholarly questions of the construction of knowledge and technology that informed some of the foundational STS studies of the 1980s and 1990s. However, the connections in future directions that we have identified here are consistent with the turns toward publics, constructive technology assessment, and politics that became more prominent in STS in the twenty-first century. They are also consistent with the attention to politics and policy that has grown in sustainability transitions research. Thus, STS and related sociotechnical perspectives for energy research are moving in a direction that is consistent with developments in STS and related fields. This parallel development is hopeful because it indicates that the use of sociotechnical perspectives in energy research will not be positioned in an intellectual silo, but instead it will be engaged with ongoing developments in related fields.

Finally, as the researchers themselves have signaled, and as our review of publications has also suggested, the benefits of illuminating parallax also can accrue to a research field that has greater diversity of social and geographical composition and of research topics. If energy social science research is to produce middle-level generalizations that can help to clarify and assist the societal goals of connecting energy systems with democracy, justice, sustainability, and resilience, then the research community and its topics of study will accrue the benefits of research that includes standpoints located outside the wealthy, industrialized countries and the privileged groups in those societies.

In summary, this review has identified three compelling and crosscutting areas of future research: studies that more explicitly and consistently seek to integrate and balance agency, structure, and meaning and that explore the broader assumptions that connect energy changes and societal changes; research that uses comparative analysis and mixed methods to improve rigor and generalizability; and topical selection that can help to contribute to the need for gender, racial/ethnic, geographical, and other forms of diversity. We especially encourage research using sociotechnical perspectives on energy and climate to branch outward to include a vaster and more diverse lexicon of case studies and to consider co-creation of research with diverse communities. We need broader work that recognizes local researchers who address very significant and practical problems in these diverse locations and research that is locally grounded yet globally relevant [446]. We also need work that is transdisciplinary (engaging non-academic stakeholders and locally impacted persons) rather than work that is merely academic and interdisciplinary [447]. Although a field as self-reflexive and constructivist as STS is usually reluctant to offer any definitive set of guidelines, we do present a series of more concrete recommendations in Box 1 intended to help researchers better address these concerns in practice.

Box 1
Practical recommendations for future STS research design.

Although researchers should feel free to violate these rules rather than do anything barbarous, we do offer a small number of common recommendations that we believe can improve the impact, rigor, inclusivity, replication, usability and humility of STS related energy and climate work. At the beginning of the process, when writing proposals or thinking of ideas or studies, we suggest that researchers consider:

1. **Social impact:** Aim for research that addresses real and pressing problems, rather than engaging in theoretical debates only.
2. **Rigor:** Execute comparative or mixed methods research designs, to be more rigorous or generalizable.
3. **Inclusivity:** Promote inclusivity and pluralism in author or project teams by social identity, discipline, geographic location, training, or methodological approach.

Then, when it gets to the point of data analysis, writing and execution:

4. **Replication:** Have an explicit research design section, for possible replication but also transparency and accountability.
5. **Usability:** Indicate what the findings imply for the action perspectives of policymakers, firms, or society.
6. **Humility:** Reflect on one's own assumptions and limitations, and preempt these actively in writing and research.

Thus, we suggest that future directions of STS and related sociotechnical perspectives as they apply to energy social science research will benefit by considering three forms of parallax: articulation with social science frameworks that traditionally have not engaged sociotechnical perspectives, articulation across the different sociotechnical perspectives, and inclusion of standpoints located outside the traditional topical preferences of research to date.

Declaration of Competing Interest

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

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Appendix I. Sample of 68 STS Studies that offered Integrated Conceptual Frameworks.

Article No.	Integrated or synthesised conceptual framework(s)
1	Prefigurative activism + imaginaries
4	Environmental knowledge cartographies + discourse analysis
5	STS + transitions + discourse analysis
6	Residual realism + relationality + systemic = ecologies of participation
9	Boundary objects + local tailoring
10	Anticipation across multiple conceptual lenses (possibly)
11	MLP + imaginaries
15	theories of practice, materiality and agency from sociology + science and technology studies
16	transitions + constructivist Science and Technology Studies (STS) perspectives on participation
17	Energy biographies which combines previous concepts
21	Fantasies + values + utopianism
29	Imagined publics + deficits models + engagement

30	Various social acceptance, trust, and citizenship heuristics
31	Material participation + energy citizenship
32	Governance + epistemic jurisdiction
34	Science Communication + Socialization
37	Expectations + fantasy + rhetoric
53	STS + social movement studies
54	A new “cosmopolitical” approach that combines previous concepts
58	Expectations + path dependence
61	STS + social movement studies
65	black boxes + regimes of imperceptibility

Note: The dataset of 68 studies appears at the following website: http://www.davidjhess.net/uploads/3/4/8/1/34811322/erss.sociotechnicalmatters.listof68articles.pdf.

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