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ADVANCED REVIEW

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# How does science and technology studies contribute to climate mitigation research? Advanced review of infrastructure as a concept and method

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## Abstract

The objective of this paper is to review how Science and Technology Studies (STS) has contributed to climate change mitigation research. We focus on large-scale infrastructures as a key topic of both mitigation efforts and recent STS scholarship. The paper assesses the conceptual and methodological treatments in this field, uses literature evidence to identify research gaps, and suggests potential topics for future research. Our research firstly contributes to the use of STS approaches in the novel field of climate change mitigation infrastructure, asking how scholarship in the field has learned from STS and developed STS further. Second, we examine how infrastructures are approached in this literature and conclude that the reviewed works almost exclusively associate infrastructure with physical supply systems. This is paradoxical since several of them also advocate a socio-technical perspective on infrastructures, which would require much more substantiation of the social aspects than they seem to provide. Third, we explore the fits between theoretical frameworks and methods in this field and discover a strong reliance on case studies, literature reviews, and theoretical-conceptual discussions. This situation suggests that methodological advancements in STS infrastructure studies has still been untapped in this area.

This article is categorized under:

The Carbon Economy and Climate Mitigation > Decarbonizing Energy and/or Reducing Demand

**KEYWORDS**

climate change adaptation, climate change mitigation, infrastructure, methodology, science and technology studies

## 1 | INTRODUCTION

This paper utilizes and contributes to advances in Science and Technology Studies (STS) to examine climate change mitigation efforts and large-scale infrastructures. In STS scholarship, the focus lies in examining science and technology as socio-material practices, highlighting scientific communities, norms, and the construction of science and technology. The core argument is that scientific evidence and consistency are negotiated, decided, and interpreted, which becomes the subject of in-depth STS inquiries (Sismondo, 2010). STS research focuses are manifold, including studies on the outcomes of science and technology, institutions, and practices, and how these are interlinked with people's lives and values (Felt et al., 2017, p. 1). Designations on STS focuses are provided in recent handbooks (Felt et al., 2017) and textbooks (Sismondo, 2010), and several commentaries from within the research field (e.g., Fuller, 1997; Sørensen, 2012, 2021).

Infrastructure studies form a pivotal part of STS scholarship, and the two fields evolved historically in conjunction with each other (e.g., Hanseth et al., 1996; Star, 1999; Star & Ruhleder, 1996). Recently, a whole infrastructure turn has emerged in the social sciences and encompasses not only STS but also anthropology (Anand et al., 2018; Wahlberg, 2022), urban studies (Luque-Ayala, 2018; Luque-Ayala et al., 2018), media studies (Plantin et al., 2018), collaborative design (Karasti et al., 2018), and sociology (Aspers & Darr, 2022) alongside evolving concepts and methods for studies of infrastructure in information systems research (Pipek & Wulf, 2009). As a consequence, infrastructure is now used in an increasing variety of contexts. In the conceptualization applied in this paper, *infrastructure* refers to any robust, widely shared, essential, and widely accessible services encompassing people, tools, and institutions (Edwards, 2010; Plantin et al., 2018), such as electricity supply and transportation, but also more knowledge-oriented infrastructures such as data infrastructures and the Internet. *Climate change mitigation infrastructure* designates mitigation measures that are consolidated into infrastructures—for example, Carbon Capture, Usage and Storage (CCUS), Electric Vehicles (EVs), active transport, and solar energy installations. Conversely, when the technologies examined are not widely accessible, widely shared, robust, and yet essential—for example, if they only exist in laboratories or at short-lived pilot projects with a small number of participants—we do not refer to them as infrastructures and consider them outside of the scope of the current paper.

This paper demonstrates how the topics and designations introduced above can bring important insights into climate change research. Energy and climate policies around the world have urged multiple efforts to map out potential pathways for decarbonization. To date, research on infrastructures has focused both on climate change adaptation and mitigation. In general terms, and following the IPCC (2022), we separate *adaptation* to refer to adjusting to actual or anticipated climate change events. In contrast, mitigation covers all aspects of reducing emissions of greenhouse gases. Given that integrated adaptation-mitigation strategies are often at play in particular sites of infrastructure maintenance, such as cities (Solecki et al., 2019), it is not straightforward to conclude whether mitigation research outnumbers adaptation research on infrastructures or vice versa. Some infrastructure research around climate change has focused on climate adaptation (e.g., Lindgren et al., 2009; Nicholls & Kebede, 2012; Rosenzweig et al., 2007), but climate change mitigation is an essential part of infrastructure design and emissions reductions. This reduction encompasses transforming the supply of energy, reductions of energy demand, and using technologies that remove greenhouse gases already at their origin. These mitigation processes target multiple relevant infrastructures, including power plants, supply chains, the petrol industry infrastructure, and transportation, to name just a few.

STS research can contribute to the scholarly debate on these topics in several ways. First, climate change is ubiquitous globally, but fresh perspectives are needed to raise public awareness of its impacts. In this paper, we suggest that climate change impacts are traceable through the study of climate change mitigation infrastructures by using the distinguished STS focus on infrastructures. Second, while infrastructure, mitigation, and adaptation are complex concepts and have many designations, an STS approach attunes our examination into how they are actually being used by scholars: focusing on the outcomes of science and technology, including how scholarship constructs these terms, presents the research methods necessary, and attaches climate change and infrastructures to real-world processes such as stakeholder engagement and public participation. Third, STS plays a role in enhancing reflexivity in climate change research. For STS, all knowledge production and use are situated within specific contexts, which also opens up the possibility of examining how societal inequalities (such as gender, ethnicity, region, or others) may be reinforced in scientific and technological knowledge.

The review proceeds to study these problems via the following structure. We first introduce our review protocol and then move to the results corresponding to the aims above. The core part of the review categorizes the STS approaches

used in the field of climate mitigation infrastructure. We then discuss the results and ask what infrastructure has meant for this scholarship conceptually, including the theory-method fits of the reviewed articles. The final part concludes with a research agenda for future studies, which follows from the findings. We argue that there is a need for further theoretical-conceptual development in this field, the infrastructure concept needs to be made more socio-technical and processual to tune in with infrastructure studies in STS, and there are methodological advances in infrastructure studies that are not yet utilized to their full potential.

## 2 | REVIEW PROTOCOL

The review protocol departed from the PRISMA 2020 review method, which is short for Preferred Reporting Items for Systematic Reviews and Meta-Analyses.[1] We adjusted the method following other recent modifications and for similar rationales (Andersen, 2022). First, while there is a vast and ever-growing literature on climate change and infrastructure, the academic literature at the intersection of climate change mitigation, infrastructure, and STS is still very small.[2] Second, this situation might suggest looking for conference papers, textbooks, websites, and other gray literature for further materials, but they are not included in the main scientific databases. With these restrictions in mind, we chose to focus our approach on scholarship on climate (change) mitigation and infrastructure and then manually include those works that utilize an STS perspective as we recognized it. The information was searched from Scopus and Web of Science to complement each other and utilize the broadest coverage and inclusion of social sciences and humanities journals, books, and chapters.

The search strategy involved first identifying all the results for Scopus and Web of Science for the two key terms of "climate change mitigation infrastructure" and "climate mitigation infrastructure." The results are summarized in Table 1. A result of this approach is that our protocol will identify many conceptualizations of infrastructure as we started our examination of how the topic is directly used in scholarly work. However, when selecting the works, the research acknowledged our working definition of infrastructure as durable and well-established services, drawing upon Edwards (2010) and Plantin et al. (2018), and this designation ended up compatible with the works discovered. This was especially the case when they addressed physical durable services, though the social components of these provisions were much less frequently emphasized, as we discuss in our findings.

The inclusion criteria were that the work selected had to include an STS-aligned perspective. We developed a wide interest in both conceptual and real-world contributions, which followed from the field's main recent textbooks and handbooks (particularly Felt et al., 2017; Sismondo, 2010) and field-specific discussions from scholars (Fuller, 1997; Sørensen, 2012, 2021). We have chosen, and demarcated, research works that satisfy one but preferably more than one of the following criteria:

- *Integration of social and technical perspectives in climate change mitigation*: This focus involves combining social, behavioral, technical, and scientific aspects to address climate change, hence reflecting the socio-material practices that constitute science and technology.
- *Social construction of science and technology*: This focus explores how various objects, ranging from devices and artifacts to facts and public issues, are socially constructed. It highlights the role taken by scientific and technological communities and norms in this active construction. It also includes examining how the constructed objects are made to apply in real-world processes.
- *Direct reference to key STS concepts and methods*: This criterion states that the source must incorporate concepts that are used in recognized STS journals and books, such as scientific paradigms, governmentality, transitions, and socio-technical systems perspectives.
- *Self-reflective approach to the conduct of science*: This focus emphasizes the need to explain the production of knowledge by social sciences and humanities approaches, thus also reflecting on the authority of scientific and

**TABLE 1** Results for "climate change mitigation" infrastructure and "climate mitigation" infrastructure, April 12, 2023.

| | "Climate mitigation" AND infrastructure | "Climate change mitigation" AND infrastructure |
|---|---|---|
| Scopus | 159 | 564 |
| Web of Science | 193 | 574 |

technological knowledge and its entanglements with the situations that people inhabit, including their values. This dimension includes the potentiality of acknowledging how ethnicity, class, gender, and alternative or marginalized knowledge systems are visible in knowledge production. However, as we demonstrate below, there is a visible lack of evidence of STS works in this area that engage with such a perspective.

After we removed the duplicates, the four authors of this paper collectively surveyed around 180 key texts. The two search term categories in Table 1 were used differently due to the corpus sizes: with the smaller amount of scholarship on "climate mitigation," all of the works were reviewed entirely. In contrast, with "climate change mitigation" research a preselection of STS-related works was conducted first before the more thorough review work began. The authors reviewed the abstracts, keywords, and main texts of each of these selected pieces. One primary reviewer was assigned to each text, but this choice was peer-reviewed by at least one other reviewer. The works were gathered in a spreadsheet, including several pieces of information along with DOIs. The reviewers all annotated the works based on what elements from STS are used, what notion of infrastructure is used, how climate mitigation is understood, and what methods are used. The result of this selection was a sample of 23 dedicated and distinguished articles, chapters, and books, which we will detail below. However, we will also return to the larger selection when necessary due to the limitations of this smaller corpus.

## 3 | SURVEYING CLIMATE MITIGATION INFRASTRUCTURE RESEARCH IN STS

### 3.1 | Identifying themes

In reviewing the articles, we identified cross-cutting themes. The STS works were grouped into broad categories, starting from more theoretical and moving towards more applied works and summarizing their main ideas. The difference is more of degree than kind, and we chose to reflect in the order in which we discuss the themes, starting on the theoretical end and moving to the applied.

### 3.2 | Key theoretical-conceptual engagements from STS

#### 3.2.1 | Controversies, governance, and public understanding

Several works reviewed here have aligned STS with the study of public issues and governance. While STS encompasses a diverse range of traditions and contains all kinds of in-depth studies of science and technology also when no publicly visible issues are apparent, the work on energy and climate research has closely aligned itself with the studies of controversies, governance and the public understanding of these issues (Hess & Sovacool, 2020; Sovacool & Hess, 2017). As we highlight below in Section 3.3.1, this interest encompasses both theoretical directions and applied interests in improved participation. Here, we first concentrate on the former. Socio-technical governance and governmentality perspectives are included in these, and studies in the field often dwell on the interpretative tradition of STS and metaphors that stem from that, such as scientific paradigms and socio-material change.

Utilization of these perspectives can be illustrated through three key studies identified in the reviewed works. First, Martinez (2022) builds an analytical tool from the interpretative tradition of STS, referring particularly to the models of Social Construction of Technology (SCOT) developed by Pinch and Bijker (1984). SCOT, originally from science studies but extended to examine technology, argues that technological artifacts have interpretative flexibility: different relevant social groups interpret the meanings and even the designs of artifacts in distinct ways, which often results in controversies. Using SCOT, Martinez (2022) examines fossil-fuel-based energy systems in Mexico. He focuses on the active interpretation of the devices for governing these systems—particularly in law and social impact assessments—by different relevant social groups and studies interpretations also after their initial designs, hence extending SCOT to institutional terms. The understanding of climate change mitigation is transformed by this interpretative process: it is shaped by the existing infrastructure-related interpretations, including top-down management, centralized decision-making, and energy sovereignty, typically held by state-owned energy companies.

Schwanen et al. (2011) utilize a similar approach to study climate change mitigation but focus on transport and start from a more scholarly critique: to date, positivistic and quantitative analysis prevails, mainstreaming a focus on price changes, physical infrastructure, technologies' improvement, and behavioral change. The authors analyze transport research as a scientific paradigm similar to those described by philosopher Thomas Kuhn (1962). A paradigm is a combination of methodologies, principles, and concepts within a scientific community and provides tools for problem-solving for a particular community. In practice, the recognized transport research paradigm limits the attention to quantitative modeling and technology, where findings that do not fit these methodologies appear as anomalies that undermine the paradigmatic solutions. Adopting then a governmentality perspective, the authors claim that transport scholars' efforts in understanding climate change mitigation are both reinforcing UK societal understandings of climate change and also shaped by them. The authors point especially to ecological modernization and neoliberal governmentality in this regard and suggest alternative theories and epistemologies—such as socio-technical transitions (see Section 3.3.2)—to change the current situation.

Finally, Sareen and Shokrgozar (2022) explore what sustainability statements imply for climate change mitigation in the contexts of rurality and especially marginalized areas. With a focus on solar energy infrastructure in Rajasthan in Western India, they posit that the socio-material reconfiguration of the energy sector and power relations within institutional structures are co-evolving. This insight leads to a reimagination of existing economic paradigms toward attaining decent living services.

Although focusing on different issues and aspects of climate change mitigation, all these three analyses share a perspective on co-production (see Section 3.3.1): climate change mitigation and particularly technical decarbonization efforts do not exist in a socio-political vacuum but are constructed in institutional terms and within power relations and should be studied by taking these into account. They then criticize existing paradigms—whether corporate, scientific, or economic—as failing to grasp these interrelations and making them thus oblivious. In this way, theoretical STS approaches can become an emancipatory tool for actors to realize their societal embeddedness and ultimately to improve living conditions amid climate change.

### 3.2.2 | Critical approaches to knowledge production

Closely adhering to and critically monitoring scientific thought and practice are integral aspects of STS. The scholarship has a rich history of adopting critical perspectives, such as *feminist technoscience* and *decolonial STS*. These critical stances have also emerged in response to identified blind spots within STS itself, underscoring the reflexive stance of the scholarship. While some of the critical themes are indeed present in our selected corpus, it is important to note that they may not necessarily take a forefront position. One notable exception is Chiu and Zusman's (2019) analysis. Seeking options to align climate mitigation interventions with other societal goods, which they term "co-benefits," their review concludes that gender is often a blind spot in development programs or that interventions to engage with gender issues meet important challenges such as an absence of female role models.

The other notable exception is the analysis by Sareen and Shokrgozar (2022), which contains a thorough perspective on colonialism. They trace back the whole notion of 'development' to a self-image held in the West and recall Gandhi's conviction that ending British rule in India without an accompanying transformation of India's institutional make-up would perpetuate colonial injustices and turn out badly for the poor. In today's practice, they note that getting to build certain infrastructural functions is more a question of contacts and political influence than of technical competence. Building infrastructures responsibly thus includes responsibly building accountability. Focusing also on India, Khosla and Bhardwaj (2019) examine how cities respond to climate change in the country. They point out in their review that "climate change is also predicted to exacerbate existing social gaps of caste and gender..., class and location..., and the existing vulnerabilities of marginalized groups such as the urban poor, the elderly, children and those whose livelihoods are subject to climatic cycles such as fisherfolk" (Khosla & Bhardwaj, 2019, p. 3).

Luque-Ayala (2018) couples his multi-level and multi-scalar, power-infused focus with a more fundamental cultural critique: his study questions whether development as such must be a leading principle, as this often boils down to replicating socio-economic paradigms from the Global North (Luque-Ayala, 2018, p. 235). Instead, the traditional logics of communities in the Global South should be followed when addressing climate change adaptation and mitigation (pp. 232–234). Interestingly, with this shift of register comes a shift in the nature of infrastructures that fall in the scope of the thinking: from purely technical systems and structures to socio-technical systems that allow for different sets of logics (p. 234).

With these exceptions, the absence of further engagements with critical topics is notable, as the connection between mitigation infrastructures and inequities engendered by racialized, gendered, and class-based fault lines is comparably straightforward to see. To see whether some works were addressing these themes in our selection, the authors revisited the broader corpus of around 180 works and searched for terms "gender," "feminism," "race," and "colonialism." While a small number of works did talk to these themes when addressing infrastructures and climate change mitigation, we concluded that none of them applied or contributed to the scholarship in STS. Hence, the initial selection of works to analyze was vindicated. In fact, a few borderline cases that emerged were still situated as part of other disciplines and, importantly, were highly focused on studying policy analysis and not primarily focused on science and technology or their combination. This represents a gap in knowledge and informs a broader concern for STS to pick up when engaging with climate change mitigation infrastructures.

### 3.2.3 | Socio-material and multi-dimensional approaches

Even when not frequently addressing alternative knowledge systems in this area, as we argued above, STS scholars frequently talk about power and politics. However, the meaning is often distinctive. Societal structures, social order, and political power are not merely distributed by the actions of people (Law, 1991). Nor are they completely explained by discourse, values, laws, and policies. Instead, STS accounts are particularly attuned to the role that technological artifacts such as devices, buildings, and software—and even whole infrastructures—play in the distribution of power. What thus emerges is a socio-material political order, which is neither purely social nor technical in its maintenance. This comprehensive socio-material approach becomes particularly visible with infrastructures. Several of the works discussed develop perspectives to address this issue.

A need for a socio-material and multi-dimensional approach to examine climate change vis-à-vis (transformations of) infrastructures is highlighted in some of the reviewed articles. Luque-Ayala et al. (2018, p. 1), for instance, start by depicting an infrastructural change: addressing "unprecedented risks and challenges resulting from climate change... will require fundamental transformations in the infrastructures that sustain everyday life." To investigate this transformation of vital infrastructures, a comprehensive update of current research approaches is needed. In other words, transitions and transformations should not be approached "solely as technical, infrastructural or systemic shifts, but also as a way of thinking about collective futures, societal development, and governing modes—a recognition of the political and contested nature of low carbon urbanism" (Luque-Ayala et al., 2018, p. 1).

In another key text of the already reviewed corpus, Martinez (2022) focuses on energy transition (ET) (see also Section 3.3.2) by utilizing a similar combination of socio-material and multi-dimensional approaches. For him, the required comprehensive framework is built by "problematizing and shedding light on the production of knowledge, innovations, and development paths for ETs and their interplay in social and material domains" (Martinez 2022, p. 2). Building on this approach, Martinez's study then "indicates that climate change mitigation and the social effects of renewables have come to shape infrastructures" (Martinez 2022, p. 2).

The shaping of infrastructures is a power-laden process. STS typically approaches power as resting in and operating through networks (Law, 1991), and this implies a complex socio-material and multi-dimensional approach to infrastructural transformation vis-à-vis climate change. Holmgren (2013, p. 369), for instance, utilizes a sociology of knowledge approach to study the global "discursive ordering of knowledge" in forest use and forest, which in turn produces "subjects, objects and activities with different rights, responsibilities and values." In a similar vein, Luque-Ayala (2018, p. 236) aims to open

> a space for plural and multiple vernacular interpretations of the *whys* and *hows* of a post-fossil world: from the need to adopt social objectives to a drive to put in place a new relationship with the natural world...or, from repositioning subjects within the infrastructural configuration of the city to constituting urban infrastructures through collective means and advocating for different ethical and economic relations in the process of accessing and allocating resources.

In the reviewed corpus, socio-material and multi-dimensional approaches are also complemented by discerning different levels in the analyzed phenomena and processes. Addressing such questions as "what environmental governance arrangements under transition reveal about the recursive relationship between socio-material reconfiguration of the

energy sector and co-evolving power relations and institutional structures" requires "multi-level institutional analysis" (Sareen & Shokrgozar, 2022, p. 1). Such an analysis encompasses:

i. *global* energy politics and their impacts;
ii. *national* and sectoral policies;
iii. *regional* operationalization of these policies via institutions and infrastructure;
iv. *local* implementations by rural energy suppliers.

Luque-Ayala's (2018, p. 236) study discusses similarly the "re-territorialization of resource and economic flows (favoring local flows over national and global circulations) and the promotion of novel environmental and 'infrastructural' subjectivities" while Holmgren (2013) inquires into global, discursive governance arrangement in the making in the climate–deforestation nexus.

The relationships between knowledge production, technological innovation, and power dynamics are typical subjects in STS inquiries. These theoretical-conceptual understanding set the stage for more pragmatic issues, including exploring stakeholder involvement and inclusion. Such an involvement is never purely practical but also triggers wide political-theoretical debates on democracy and governance of science and technology, as we discussed in the following sections.

## 3.3 | Practical engagements in science, technology, and society

### 3.3.1 | Stakeholder engagement

Over the past decades, an important fraction of STS has paid attention to the involvement of stakeholders in processes of innovation and its governance (Chilvers & Kearnes, 2020; Ryghaug & Skjølsvold, 2021). Some of this has branched out to more political-theoretical debates on democracy and citizenship (Ryghaug et al., 2018; Silvast & Valkenburg, 2023), and other contributions have rather focused on the development of more practical tools and approaches for stakeholder involvement (Welp et al., 2006). The literature emerging through our search criteria contains a body of research on such stakeholder engagement. The notion of *co-production* is sometimes used in this respect, but not always, and it needs stipulating that co-production means two very different classes of ideas in STS. The foundational-conceptual version holds the understanding that our lifeworld, as constructed through the technoscientific interventions we make in it, evolves together with our ways of understanding that very world (Jasanoff, 2004). The more practical version explores ways to make sure that policy, technologies, and other interventions align with the needs and interests of the stakeholders that need to support the interventions by enrolling those stakeholders in processes of design and decision-making (Turnhout et al., 2020; Upham et al., 2016).

In our sample, especially this latter, intervention-oriented notion of co-production emerges, together with some account of how stakeholders matter or should be made to matter (Boyle et al., 2022; Chiu & Zusman, 2019; Feldpausch-Parker et al., 2018; Khosla & Bhardwaj, 2019;Toxopeus & Polzin, 2021; Upham et al., 2018). In multiple publications, this stakeholder engagement naturally relates to the connection of infrastructural, mitigation, and adaptation issues to the social-geographical notion of *place*, whether in general (Toxopeus & Polzin, 2021; Upham et al., 2018) or specifically related to cities and urban life (Khosla & Bhardwaj, 2019; Soloviy et al., 2020), or rural development (Sareen & Shokrgozar, 2022). The purpose of stakeholder engagement and co-production ranges from a narrow (by which we do not mean less important) understanding that is limited to acquiring the visions and perceptions of citizens (Feldpausch-Parker et al., 2018; Upham et al., 2018) for the purpose of gaining acceptance and a good socio-technical 'fit,' towards more comprehensive approaches and methods to disseminate information, develop rules, provide demonstrations, explore new policy practices, among others (Boyle et al., 2022; Chiu & Zusman, 2019; Westman & Broto, 2018). Stakeholders are not necessarily individual people but also companies, foundations, research communities, NGOs, and non-profits in general (Hallosserie et al., 2019). *Public-private partnerships* in financing are an important strategy to enroll those non-individual entities (Chiu & Zusman, 2019; Toxopeus & Polzin, 2021).

It is striking that all publications that we found and classified as relating to stakeholder involvement and co-production treat infrastructures, climate change mitigation, and climate change adaptation as a generic backdrop rather than concrete, specific technologies and techniques to be interrogated. On the one hand, this signals that additional STS research might be done that focuses in more specificity on particular technological interventions, such that

the unique relations between human beings, infrastructures, and notions of climate change mitigation and adaptation are studied in more detail, be it perhaps at the cost of generalizability. On the other hand, that such research has not yet emerged, even though it would be relatively straightforward from mainstream STS perspectives, might signal that the concerns of mitigation are insufficiently framed as broader societal *issues* (Marres, 2005, 2007) rather than technical issues (Kongsager, 2018) on which stakeholder engagements actually emerge.

### 3.3.2 | Sustainability transitions research

The five papers in this category are situated in sustainability transitions research: the study of how our socio-technical systems can be understood and transitioned to more sustainable pathways (Köhler et al., 2019). In particular, they examine the interplay between transport, climate change, and urban governance and include the subthemes of social studies of technology, transition studies, and sustainable lifestyles. Bakker et al. (2014) highlight the need for an integrated framework that addresses the complex relationships among transport, development, and climate change mitigation. They suggest that the existing Avoid-Shift-Improve (ASI) approach should be expanded to incorporate transition theory, sustainable lifestyles, and the concept of Access, as it then offers a more comprehensive and sustainable view of the transport sector. Another work (Castán Broto & Bulkeley, 2013) emphasizes the significance of experimentation as a governance strategy in addressing climate change in urban settings. They analyze a global database of urban climate change experiments to uncover the diverse mix of actors, settings, governance arrangements, and technologies involved. Experimentation is advocated as a crucial tool for understanding the practical implications of interventions and opening new political spaces for climate governance.

Kern and Rogge (2016) address the question of the pace of energy transitions in the context of climate change mitigation. Through historical analysis and examination of current governance efforts, they argue that transitions towards low-carbon energy systems can be accelerated by active governance, international innovation dynamics, and the political will reflected in the global Paris Agreement. Another study (Rosenbloom, 2018) explores the role of discourse in shaping low-carbon pathways, which reveals how contending actors frame issues and technologies, influencing the choices and sequences that lead to sustainable futures. They emphasize that negotiation among competing interests and the importance of regulatory measures in accelerating transitions. Lastly, Affolderbach and Schulz (2016) advocate for an integrated approach that incorporates urban and economic geography perspectives, which is an approach that highlights the relational nature of innovations, the significance of policy mobility, and the agency of individual actors in driving sustainable urban transformations. Overall, these papers contribute to a deeper understanding of the complex interactions between technology, governance, and sustainability and provide valuable insights for policymakers, researchers, and practitioners working towards sustainable urban futures.

## 4 | DISCUSSION

The STS-related works reviewed contain several relevant insights on publics, governance, socio-materiality, multi-level perspectives, stakeholder engagement, and transitions as elements of climate change mitigation and infrastructures. In examining this literature together, though, certain key research gaps, limitations, and avenues for further research also emerge. We have summarized our literature findings in Table 2 and now discuss them in order: the theoretical use of the concept of infrastructure and, relatedly, methodological concerns in STS of infrastructure.

### 4.1 | Infrastructure as an approach and not an object

In the reviewed corpus, infrastructures were approached in general as physical supply systems: that is to say, durable and wide-ranging networks that comprise the material underpinning of everyday practices. Examples included supply chain infrastructures (Chimner et al., 2017), Electric Vehicle infrastructure (Heidrich et al., 2017), electricity infrastructure (Feldpausch-Parker et al., 2018), and low-carbon energy systems (Solecki et al., 2019). No infrastructural approach in a strong sense of the term, such as Actor-Network Theory (ANT) or similar frameworks focusing on "infrastructuring," were utilized. However, in some articles and chapters (Luque-Ayala, 2018; Luque-Ayala et al., 2018; Martinez, 2022; Sareen & Shokrgozar, 2022), a somewhat deeper conceptual understanding and framing was at play: in

**TABLE 2** Reviewing STS research on mitigation, adaptation, infrastructure, and methods.

| Reference | Climate change mitigation | Climate change adaptation | Studied infrastructure | Method/approach |
|---|---|---|---|---|
| (Affolderbach & Schulz, 2016) | The role of cities in climate change mitigation | Adaptation used several times, but not in relation to climate change | Alternative energy and transportation infrastructure | Theoretical work seeking synergies between urban sustainability research and transition studies |
| (Bakker et al., 2014) | Used in regard to lowering GHG emissions from transport | | Transport infrastructure and services; economically viable infrastructure and operation | A review of current perspectives and practices on transportation and sustainable development, framework development |
| (Boyle et al., 2022) | Explores the role of citizen and community engagement in climate mitigation projects | | Climate infrastructure development projects | An action research approach using mixed methods, including interviews and an online participatory workshop |
| (Castán Broto & Bulkeley, 2013) | A survey of urban climate change experiments in 100 cities, inclusive of climate change mitigation and adaptation | See left | Urban infrastructure including built environment and transport | Survey evidence from a database of 627 urban climate change experiments in a sample of 100 global cities. |
| (Chimner et al., 2017) | GHG sequestration in wetland restoration projects | Adaptation used to the environment, but not specifically in regard to climate change | Impacts on peatlands from roads and petrol industry infrastructure | Review article |
| (Chiu & Zusman, 2019) | Mitigating climate change as a development priority | | Financial and economic barriers recognized in cases involving infrastructure | Comparing 28 case studies from 5 sectors in 10 Asian countries |
| (Feldpausch-Parker et al., 2018) | Identification of discursive patterns of electricity stakeholders related to climate mitigation and adaptation in the aftermath of Superstorm Sandy | See left | Energy and critical infrastructure system vulnerabilities, especially electricity supply | An in-depth case study that assesses discourses in stakeholder groups by using focus groups |
| (Hallosserie et al., 2019) | Questions whether the benefits of the energy transition in terms of climate mitigation is not actually contributing to further accelerating the erosion of biodiversity | Mentions climate change adaptation a few times but does not focus on it | Renewable energy infrastructures, the impacts that infrastructures reliant on different power sources have on biodiversity | A document analysis based on literature, a proceeding, and a guide |
| (Heidrich et al., 2017) | Used in regard to climate change mitigation strategies by promoting the uptake of ultra-low carbon vehicles for road transport | Highlights specific plans in regard to how cities will adapt to climate change | Electric vehicles (EV) and their charging | Analyses climate mitigation strategies and supporting documents from 30 UK cities, focusing on EV registrations and the EV infrastructure data that is provided by cities |

(Continues)

TABLE 2 (Continued)

| Reference | Climate change mitigation | Climate change adaptation | Studied infrastructure | Method/approach |
|---|---|---|---|---|
| (Holmgren, 2013) | Reduce GHG emissions from deforestation and degradation of tropical forests | Adaptation is described as a development priority where the main objective is to decrease vulnerability to storms, droughts, and floods | Abstract institutional–organizational infrastructures | Utilizes the sociology of knowledge approach to discourse (SKAD) to analyze the production of REDD +discourse in four REDD+ program documents |
| (Kern & Rogge, 2016) | Climate change mitigation targets and the pace of energy transitions and decarbonization processes | | Fossil fuel infrastructure | Short communication and perspective piece |
| (Khosla & Bhardwaj, 2019) | Investigating climate change mitigating and adaptation efforts in Indian cities | See left | Infrastructure services, infrastructure planning, local transit infrastructure, infrastructure systems | Synthesizes and characterizes the emerging literature on Indian urban climate debates |
| (Luque-Ayala, 2018) | Low carbon urbanism in the post-development process in the global South | Mentions climate change adaptation a few times, but it is not the key focus. | A multi-dimensional and critical approach to energy infrastructures and development work | Analyses discourses based on literature |
| (Luque-Ayala et al., 2018) | Low carbon transition in urban systems | | General focus on the physical infrastructures that sustain everyday life (e.g., energy, water, waste collection, mobility) | [Not specified as it is a book introduction] |
| (Martinez, 2022) | Energy transition to renewables and focus on the social effects of doing this. | | A multi-dimensional approach to energy infrastructures from a general point of view of energy transition | Process tracing, in-depth case study with mixed methods (participant observation, semi-structured interviews) |
| (Rosenbloom, 2018) | The role of cities in climate change mitigation. Studies the phase-out of coal-fired power in Ontario | | Energy infrastructure (coal-fired power plants) | Drawing on discourse perspectives, this study deploys the multi-dimensional discursive approach, using media articles as materials |
| (Sareen & Shokrgozar, 2022) | Implementation of lower-carbon energy infrastructures (solar energy) for climate mitigation | | New lower-carbon energy infrastructures (solar energy), socio-material infrastructures | A literature-based case study |
| (Schwanen et al., 2011) | Scientific paradigmatic engagements with climate change mitigation in transport are studied. | | Transport with a particular focus on transport systems and physical infrastructure provision | Literature review |

TABLE 2 (Continued)

| Reference | Climate change mitigation | Climate change adaptation | Studied infrastructure | Method/approach |
|---|---|---|---|---|
| (Solecki et al., 2019) | Efforts to transition toward low-carbon pathways in urban areas | Adaptation to climate-related extreme events | Low-carbon economy and infrastructure, institutional infrastructure, urban infrastructure, public infrastructure, energy supply infrastructures | Framework development work based on four empirical case studies |
| (Soloviy et al., 2020) | Carbon sequestration by forests in urban environments | The role of forests in urban environments in adapting to climate change | Concrete urban infrastructures | An integrative critical review of 44 articles published during the 2000–2020 period |
| (Toxopeus & Polzin, 2021) | Nature-based solutions (NBS) solutions to provide climate change mitigation and adaptation | See left | Infrastructure investments, green, blue, and gray infrastructure | Discusses strategies found in the literature that address barriers to obtaining public and/or private finance for upscaling urban nature-based solutions |
| (Upham et al., 2018) | How the willingness for the implementation of local climate change mitigation measures are impacted by place attachment | | Renewable energy infrastructure, energy, and climate mitigation infrastructure | An opinion note with an interdisciplinary change readiness hypothesis, which includes a local participatory scenario and visioning processes |
| (Westman & Broto, 2018) | Investigates governance strategies in urban climate mitigation action in China | | Public service and public infrastructure | Exploratory qualitative analysis of governance in urban China through analysis of a database of 150 climate initiatives in 15 cities |

these texts, infrastructures were approached as power-laden socio-material and multi-scalar arrangements, and rather problematized than depicted as blunt objects. Luque-Ayala's (2018, p. 234) interpretation is rich in this regard:

> Infrastructure takes the form of knowledge transmission via social networks, and energy is seen in the context of subject rights (to solar energy) and duties (to transmit solar energy knowledge). The emerging energy arrangement upsets traditional power balances—and its respective financial flows—between central (e.g., national and regional utility companies) and local levels (dwelling and municipality), opening possibilities for new scalar configurations and understandings of the role of the city in relation to the state.

Sareen and Shokrgozar (2022, p. 8) share a similar multidimensional approach to infrastructures and have also developed some "bridging concepts" to study solar energy systems as actor-constructed technologies.

In fact, there is a large line of research in STS that has taken the processual character of infrastructures a step further and highlighted infrastructures as a process and dynamic, not as static and obdurate (Kragh-Furbo et al., 2023). It develops a more focused scope on infrastructures and especially what it names as "infrastructuring" (Pipek & Wulf, 2009) found across different settings enabling and contrasting applications and local actions. Karasti et al. (2018) draw from the heavily cited infrastructure scholarship (Star & Ruhleder, 1996) but tune it to emphasize similar points other information systems researchers (Hanseth et al., 1996), namely the perpetual processual, in-the-making quality of all infrastructures. More particularly,

> it is not that the act of building an infrastructure ever simply ratifies pre-existing relationships. The act of infrastructuring changes what it is to be a road, a unit of currency or an ecology. Infrastructures are engines of ontological change. They stand between people and technology and nature and, in so doing, reconfigure each simultaneously. Core to our vision ... has been an understanding of the perpetual refiguring which is at the heart of infrastructuring.

(Karasti et al., 2018, p. 272)

This interest brings us to anthropological perspectives, especially as the work mentioned here is strongly embedded in anthropological ethnographic methods (Karasti & Blomberg, 2018). Anthropologists do not study infrastructures as fixed systems but point out that infrastructures are active or "dense social, material, aesthetic, and political formations" (Anand et al., 2018, p. 3). Infrastructures are comprised of sites that are actively maintained and retrofitted (Howe et al., 2016). Methodologically, the recent work on this area (Abram et al., 2021; Boyer, 2015; Collier & Lakoff, 2021; Wahlberg, 2022) builds on the anthropological field study method: an ethnographer unpacks the infrastructure by being situated in the field where they manifest, usually observing how they unfold over a long duration of time. These ethnographies move between design, use, construction, state planning, inaugural ceremonies, and political discourse to expose the different sites where infrastructures are continuously enacted.

There is considerable, both conceptual and methodological, potential in utilizing these insights further to understand climate change mitigation infrastructures. This would mean framing them not as fixed and static physical systems, but as infrastructures in the making, and in doing so, focusing on infrastructurings and even re-infrastructurings of existing constellations of large systems initially built for different purposes than climate change issues. The proposed approach is also designed to consider the power dimension inherent in infrastructuring. Infrastructures are not neutral entities; rather, they perpetuate both local and global inequities and entrench colonialism by employing modernist planning and imposing Western thought forms onto local indigenous knowledges (see Lindblad & Anand, 2023). In forthcoming research, it is thus imperative to approach planning, construction and upholding of infrastructures as infused with power and to investigate how various forms of infrastructuring for climate change mitigation are intertwined with asymmetries related to class, race, gender, and knowledge, as well as the diverse intersections of these factors.

## 4.2 | Theory-methods fits and methodological ambitions

Over the past few years, methodological discussions have become commonplace in energy and infrastructure studies. The debates on concepts and methodologies in studies of infrastructure have intensified and become more systematic at the same time as the scholarship has multiplied in number and diversified in its themes. The interest spans from

prescriptions about research design and methodology (Hyysalo et al., 2019; Ribes, 2014) to reviews about typologies and conceptual frameworks in STS and socio-technical research (Edomah et al., 2017; Hess & Sovacool, 2020; Ingeborgrud et al., 2020; Köhler et al., 2019; Sovacool & Hess, 2017). Considering only the energy infrastructure, several collections of research programs have integrated social science approaches in research on energy systems and infrastructures (Ryan et al., 2014; Sovacool et al., 2015). Furthermore, several reviews have interwoven STS and socio-technical systems perspectives into other application domains, such as the range of methods to be used in policy-relevant research (Geels et al., 2019).

Recently, the discussion of the methods in this STS field has manifested around the biography of artifacts and practices (BOAP) perspective (Hyysalo et al., 2019; Pollock & Williams, 2010). BOAP emphasizes that the ethnographic field site is something more extensive than situations and practices. BOAP stresses the importance of historical context and focuses on relationships that it takes on from technology studies—between users, designers, and various intermediaries in between them. Following an "artifact" around, with its appropriation by different technological actors and during history, is one strategy in a multi-sited ethnography that may also want to follow people, metaphors, certain stories, plots, allegories, conflicts, or the lives of people (Marcus, 1995). It may also follow infrastructures across sites, as we have done by using regulatory formulas, residential consumers, and special control rooms as our research fields (Silvast & Virtanen, 2014, 2019).

With these developments in view, the review corpus, albeit it is relatively small and narrow, is not methodologically ambitious. The predominant research models in the reviewed STS works are reliant on review methods and literature searches, case studies, qualitative interviews, explorative qualitative analyses, and even opinion articles and thought pieces, to name a few. There are some works that rely on in-depth field research, including participant observation in expert settings (Martinez, 2022) and detailed discourse analysis (Rosenbloom, 2018), but they do not form the majority. The methodological problem is that infrastructures are complex and multi-sited assemblages that do not yield themselves to short-lived 'snapshot' studies (Hyysalo et al., 2019). There is a need for methodological depth and breadth to account for this complexity, which is a challenging task for researchers of infrastructure including those surveyed in this paper.

Reflexive discussions on methodologies are visible in STS recently, but the issues have been known since the classic texts. Star's (1999) famous work on infrastructure was also presented as an explicit method of instruction. She talked against the methods textbooks of qualitative research, which focus on localized studies, qualitative interviewing, and talk since they do not capture the dynamics of infrastructure. For instance, studies in a field site end when the interview speech is saturated but not when all the relevant standards have been studied thoroughly. This suggests that conventional textbooks (like those on ethnography) may give limited tools and tricks of trade for the social scientist studying infrastructure. As Star (1999) acknowledges, local ethnographies do not always scale up to study complex and distributed infrastructures—for example, because the infrastructure is not finished when the ethnographer gets to the site.

These methodological considerations reveal research gaps in the literature on climate change mitigation infrastructure. Suppose the infrastructure is only studied for a limited time in a single locale. In that case, this may conceal a number of dynamics that would have been visible by following the infrastructures across different sites. In a similar sense, if small-scale local experiments comment on infrastructures, then the need to expand infrastructures across multiple users and space will not be attended. Future scholars of this area, both inside and outside of STS, should put more emphasis on this methodological development work.

## 5 | CONCLUSIONS

This review aimed to improve the reflexivity of STS research and targeted both STS and non-STS experts. We sought to assess the theories and methods used in this field, use literature evidence to identify research gaps, and suggest the potential for research studies. Our research interest is critical and contributes to the advancement of STS-based knowledge in four main ways.

First, we have dwelled on the use of STS approaches in the very new field of climate mitigation infrastructure, asking how scholarship has learned from STS and developed it. The key result was a categorization of research into two main themes with different orientations: abstract/conceptual and interventional/real-world contributions. We also showed that research works in both these categories share a surprising lack of established theory-methods approaches in STS (such as Actor-Network Theory), preferring empirically driven research agendas.

Second, we asked how infrastructures are seen as deeply socio-technical constructs and include both physical systems and more abstract vital societal functions. Here, we concluded that the works almost exclusively associate infrastructure with physical supply systems, though they also paradoxically often advocate a socio-technical perspective in doing so.

Third, we have extended our previous research work (Silvast & Virtanen, 2019, 2023) and explored the fits between theoretical frameworks and methods in this field, with an aim to seek which metatheoretical underpinnings imbue this STS work and what methodologies and methods are assigned to contribute to it. We discovered reliance on case studies, review-based pieces, and even thought pieces. This situation suggests that methodological state-of-the-art in STS infrastructure studies has still been untapped in this area.

By taking a socio-technical approach to infrastructures, STS helps highlight the ability of infrastructures, and technologies in general, to destabilize and rethink taken-for-granted understandings of climate change adaptation and mitigation and how these can or should be implemented in societies. The critique of uncritically replicating logic from the Global North is one of them.

Through its aim of staying close to how involved actors define concepts, STS is comparably open to multiple definitions of adaptation, mitigation and how infrastructures relate to them. This is reflected in the divergent use of the terms in the researched literature. In consequence, STS does not by itself command a specific understanding of each of the concepts. The strength of STS's contribution, then, is in its invitation to higher-level reflection on whether challenges are (or must be) confronted through technological, political, economic, or cultural means, and how the transactions between those domains can be made more transparent.

## AUTHOR CONTRIBUTIONS

**Antti Silvast:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); project administration (equal). **Mikko J. Virtanen:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal). **Govert Valkenburg:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal). **Rico Kongsager:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal).

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## CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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## RELATED WIREs ARTICLE

Extreme events and climate adaptation-mitigation linkages: Understanding low-carbon transitions in the era of global urbanization

## ENDNOTES

[1] http://www.prisma-statement.org.

[2] A search in Scopus on "climate change mitigation," "infrastructure," and "Science and Technology Studies" gives only one result, which is the first author's monograph (Silvast, 2017). The terms "climate mitigation," "infrastructure," and "Science and Technology Studies" gives one result that we also use in this review (Martinez, 2022). A search of these terms in Web of Science produces no results. Moreover, the search terms of this article (Table 1) produced no results in the flagship and association STS journals across regions, including *Science as Culture*, *Social Studies of Science*, *Public Understanding of Science*, *Science & Technology Studies*, *Science, Technology, & Human Values*, *Engaging Science, Technology, and Society*, *East Asian Science, Technology, and Society*, and *Tapuya: Latin American Science, Technology, and Society*.

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