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The role of infrastructure in societal transformations

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The concept of 'infrastructure' has evolved to encompass the broad range of material and immaterial structures that connect, and thus enable the movement of the resources considered essential for human well-being [1]. Nevertheless, in many places of the world, infrastructure development has also been associated with economic, gender, and racial/ethnic disparities, as well as significant environmental harms, including carbon emissions, deforestation, and biodiversity loss [2-4]. No longer restricted to the so-called 'gray' infrastructure of roads, bridges, pipes, and tunnels, infrastructure now incorporates the social and political relations that shape the exchange of knowledge and information, the constellation of ecological relations that support ecosystem-service provisioning, and the rapidly evolving world of cyberinfrastructure. As the complexity of our conceptualization of infrastructure has increased, so has our understanding of the contributions of infrastructure to sustainability transformations. On the one hand, infrastructure systems have become targets of resistance and public protest, seen as perpetuating and solidifying perceived antiquated notions of fossil-fuel dependence and the prioritization of narrowly defined economic gain at the expense of social justice and environmental integrity [5,6]. On the other hand, activists, scientists, and practitioners are framing novel constellations of gray–green–blue and social infrastructure as engines of transformation to more sustainable futures [7,8]. Therefore, infrastructure constitutes both a challenge and an opportunity to transition toward sustainability. Almost by definition, infrastructure systems are transformative: by connecting dispersed nodes of consumption and demand, production and supply, infrastructure systems create self-reinforcing pathways that inexorably shape the subsequent social, ecological, and technical interactions of any system. Infrastructure thus *creates* systems, defines system boundaries, and determines who and what is central, included, and connected, and who and what is marginal, excluded, and isolated. Thus, it is not only the social and environmental impacts of the material infrastructure that matters for sustainability, but also how our infrastructures provide adequate foundations from which to create more equitable, just, and resilient futures [9]. There needs to be more elaboration of conceptual frameworks, models and comparative research to incorporate equity and mitigating power imbalances in decision-making related to infrastructural development [10].

The nineteen contributions of this Special Issue explore the role of infrastructure in and for sustainability transformations. Collectively, they highlight emerging sustainability challenges faced by our evolving infrastructure systems, explore the challenges for governance such systems pose, and posit specific strategies that can help harness infrastructure as a tool of sustainability transformation. The remainder of this editorial provides a brief summary of articles in this issue organized around five overlapping and interconnected themes: 1. scale, scope, and the meaning of infrastructure systems; 2. reframing infrastructure objectives and governance; 3. importance of foregrounding knowledge infrastructure; 4. anticipating/managing trade-offs and synergies of new and emerging

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infrastructure constellations; and 5. importance of equity, inclusion, and justice in all infrastructure processes. We conclude with some suggestions about possible future directions for the role of infrastructure in societal transformations toward sustainability.

Scale, scope, and the meaning of infrastructure systems

A number of articles provide reviews of how infrastructural systems are understood and call for reframing the *scale, scope, and meaning of infrastructure systems* to be more accountable to impacts and externalities, and more socially and ecologically just and inclusive in how problems are anticipated and addressed. The authors address infrastructure systems at distinct scales, providing contextualized insights into the salience of different infrastructure configurations for sustainability. McShane and Coffey [11] argue that vulnerability and resilience are better addressed through social infrastructure, particularly local-level community-based facilities such as community hubs, rather than engineered systems. The authors reconceptualize community hubs from service-delivery vehicles to institutions of adaptation and resilience premised on key notions at the local scale: partnership arrangements with government agencies, place-based orientations, embeddedness within socio-technical and socio-ecological systems, and interest in transitional and transformational change opportunities.

Delpino Marimon et al. [12] focus on how infrastructures linked to the transport of commodities impact and structure socio-ecological dynamics at the scale of tropical forests rather than as one-off instances of infrastructure development projects, which result in fragmented and ineffectual policies. Rather, they argue for understanding mega-infrastructure projects as assemblages of physical infrastructures and social and political interests that establish trajectories of development and interconnected social–ecological impacts over time. These 'tradescapes' help to illuminate relationships between patterns of forest change and disparate infrastructure projects, legal reforms, and trade policies across political borders.

Advancing sustainable transformations at the global scale, Gutiérrez- Vélez et al. [13] argue, requires understanding how processes across the scale of urban/rural divides shape sustainability outcomes. Conceptualizing urban and rural as coconstitutive provides an avenue to envision more sustainable infrastructure systems that integrate nature and support diverse livelihoods. Applying a 'provincializing' framework centering the global south, intersecting power relations, and historical context to the examination of infrastructures allows for a fuller accounting of how power is distributed throughout existing proximal and telecoupled systems. Such knowledge helps identify what decisions can lead to more just and sustainable infrastructure systems.

Behm et al. [14] situate biodiversity in vegetation at the urban scale as a form of urban ecological infrastructure that generates critical ecosystem services that improve the well-being of urban residents. The authors develop a species trait-based urban ecology approach to advancing research on how species and their traits provide ecosystem services through trait-service relationships and assemble urban ecological communities that can differ across urban versus more 'natural' environments. They pose a research agenda to fill critical ecological knowledge gaps of how biodiversity can promote urban sustainability for use by planners and managers.

Reframing infrastructure objectives and governance

A second theme emerged in terms of the need to *reframe the objectives and governance* structures of infrastructure systems, calling attention to a neglected area of scholarship, which is interrelated with the scope, scale, and meaning of infrastructure systems. Manheim and Spackman [15] argue that using the embodied rationality of consumers offers policymakers and practitioners an alternative framework of human action in sustainability unhindered by narrow framings that inadequately support policy solutions with greater reach. Embodied rationality assumes that individual perception is based on corporeal needs and therefore decisions are situated and relational, made at the nexus of environment and individual. Policymakers' application of embodied rationality can help them to address and engage with public perceptions when aiming for sustainable infrastructure.

Markolf et al. [16] argue that the objective of infrastructure systems should shift from an emphasis on efficiency toward resiliency, the latter understood as a public good. This would enable the establishment of standards and policies to control negative externalities in a manner similar to how governments seek to manage air and water quality. Drawing on recent advances in ecological and social sciences, the authors suggest novel approaches to navigating this tension, such as incorporating exploratory models and stakeholder coproduction in the design and implementation of infrastructure systems in order to better understand system thresholds and the socio, ecological, and technical contexts.

Monstadt et al. [17] synthesize four emerging transformative approaches to the governance of urban infrastructural change to understand both their potential and points of convergence and contradiction. The first 'futures' pertains to assessing alternative infrastructural pathways, followed by 'experimentation' wherein infrastructure pathways are enacted and, 'cross-domain coordination' and 'assessing for transformative change' which each provide support to these transformations. The authors call for increased dialog among the approaches while urging attention to context and power dynamics in order to enable more equitable and sustainable infrastructure systems.

Importance of foregrounding knowledge infrastructure

A third theme that emerged throughout the Special Issue is the *importance of foregrounding knowledge infrastructure* as central to reconceptualizing what infrastructure is and does, as well as how infrastructure governance can enable more equitable processes and outcomes. Pearsall et al. [18] argue for the need to account for asymmetries in power in efforts to design infrastructure systems in multilevel governance conditions. Scaling up knowledge coproduction efforts is critical and requires 'knowledge infrastructures' that can account for complex power asymmetries within stakeholder communities. The authors propose principles to guide the development of knowledge infrastructures that can delineate the values, relationships, and power dynamics among different actors involved in the production of knowledge at different spatial scales.

Babbit et al. [19] argue that food waste in the United States, with its immense climate and ecological impacts, can be leveraged to achieve sustainability goals through circular economy strategies. Such strategies require the coevolution of physical and human infrastructure along with data and computational infrastructure that are needed to account for the complex interrelations of physical and human infrastructure. Doing so will require the coproduction of knowledge, which although challenging, can produce insights transferable to the study of other complex infrastructure systems.

Bojórquez-Tapia et al. [20] argue the utility of Decision Making Under Deep Uncertainty (DMDU), a set of computational practices, to identify and explicitly address the diversity of inherent uncertainties in large-infrastructure projects, especially when integrated with knowledge coproduction practices. DMDU can help diverse actors grapple with uncertainties, illustrate system complexity and tipping points, and illuminate engrained structural barriers and path dependencies. The authors use recent empirical work in Mexico and Vietnam to illustrate the utility of DMDU to assist decision-making for more sustainable transformations.

Aleida et al. [21] argue for broader strategic planning of hydropower infrastructure using advances in data availability and computational analysis to expand the spatial scale of planning to improve both economic and socio-environmental outcomes. Currently, the process of siting these projects is largely driven by political and economic considerations and done on a single-project basis. With increasing demand for renewable energy sources, greater emphasis will be placed on developing hydropower infrastructure representing a serious threat to global biodiversity and regional economies. The lessons learned from strategic hydropower planning through advances in data science can be applied to other networked energy-system planning.

Anticipating/managing trade-offs and synergies of new and emerging infrastructure constellations

A fourth theme emerged about *anticipating and managing trade-offs and synergies of new and emerging infrastructure constellations* toward more sustainable social–ecological–

technological systems (SETS). The authors connect these decisions to the need for knowledge infrastructure as well as governance and coproduction challenges. Branny et al. [22] argue that thinking about smart-city initiatives through SETS lens will improve considerations of ecological processes and social equity and justice in the process. The development of 'smart cities' and application of big data is frequently cited as a benefit to sustainability. However, because of the technology-centered nature of these approaches, they frequently fail to account for the complex interactions between social and ecological components of urban systems.

Gim and Miller [23] demonstrate that institutions are key social components that create interdependencies in SETS and therefore deserve increased attention in efforts to map the vulnerability and resilience of complex, multi-infrastructure systems. This requires extending analyses of infrastructure resilience beyond engineering assessments of physical interdependencies to include the social and environmental linkages that often create both new forms of vulnerability in interdependent systems and can lead to pathways of cascading failures. The authors propose a framework for institutional analysis that differentiates institutional interdependencies.

To manage trade-offs and enhance the potential for synergies among competing values associated with Urban Green Infrastructure (UGI), Depietri [24] emphasizes the need for engaging in deliberative, proactive societal engagement and data collection in UGI planning and maximizing the potential for multifunctionality and co-benefits. The author categorizes trade-offs with UGI: ecological, socioeconomic, technological, and in relation to governance/ institutional, finding the latter two categories as emergent domains of increased attention. Depietri suggests pulling back from framing UGI as an alternative to conventional gray infrastructure and instead exploring the potential of a more hybrid approach.

Andersson et al. 25 propose a framework to evaluate hybrid infrastructure-design contributions to urban resilience against extreme events. The framework includes various components that can provide multiple, consecutive, or complementary layers of resilience. The authors use the notion of hybridity to capture the relationships between structures and processes inherent to ecosystems and the built environment. While integrated green and gray systems offer a greater diversity of functions and services, such diversity requires the involvement of more actors and a broader knowledge base, presenting governance challenges in the form of coordination and integration.

Kim et al. [26] argue for an approach to infrastructure planning and design that can effectively utilize safe-to-fail concepts by navigating the opportunities and trade-offs present in a social, ecological, and technological system's resilience capabilities. A safe-to-fail approach challenges the common reduction of complex systems in that it requires planners to identify potential impacts of failures across a SET system and navigate the trade-offs in the design process. It opens up opportunities and challenges for collaborative and inclusive governance, including determining who is responsible for navigating trade-offs and how to engage stakeholders.

Importance of equity, inclusion, and justice in all infrastructures

Throughout the Special Issue, the reviews of infrastructure and sustainability insist on the *importance of equity, inclusion, and justice in all infrastructure systems and processes*. How and at what scale we conceptualize infrastructure, reframe governance, create and utilize knowledge infrastructures, and consider trade-offs are inextricably intertwined with imagining and building more inclusive, just, and equitable sustainable futures. Steele [27] contends that key to achieving sustainable development is recognizing the trajectory and legacy of the unsustainability of past development paradigms. The author argues for new paradigms of social and ecological commons to build infrastructure futures that are ecologically balanced, community-oriented, and culturally sensitive. This involves repoliticizing the role of urban infrastructure and extractive development processes. Steele examines the contested role of 'wild' infrastructure to recognize vulnerability and interconnectedness, but also the necessity of regenerative practices that involve working with communities from the ground up.

Soliz and Pérez-López [28] advocate for re-examining infrastructure investments that reinforce mobility injustices using the example of urban pedestrian bridges. While ostensibly designed in order to ensure pedestrian safety, such bridges present significant issues related to accessibility, which reinforces existing mobility injustices predicated on the privileging of motor-vehicle traffic. Foot bridges demonstrate the imperative for further research into inclusive and situated approaches to sustainable transitions for transportation infrastructure and particularly the role pedestrian rights activism can play in sustainable transportation alternatives.

Fatti [29] uses the example of government-led housing in South Africa to argue that justice and sustainability should be understood as potentially conflicting rationalities that require deeper engagement with the decision-making process and rectifying the power imbalances that hinder coproduction. The author argues for conceiving of just sustainability as a hybrid concept, wherein justice and sustainability are understood as potentially conflicting rationalities. Fatti posits that

conflict should be accepted and taken seriously in order to achieve long-term progress toward sustainable development goals. Furthermore, just sustainability requires deeper engagement with decision-making processes and the ways in which knowledge and power are used to influence outcomes and hinder coproduction.

Future research directions

As the Special Issue illustrates, research on the role of infrastructure systems in achieving sustainability has been a highly fruitful line of inquiry, but there is clearly more research needed to understand how the meaning of infrastructure systems is evolving as the scope, scale, and functions of social–ecological–technical systems change. Specifically, more attention is needed on the role of novel infrastructure systems in the pursuit of more sustainable futures, how they can be equitable and inclusive, and what governance structures and processes will achieve these goals. The authors highlighted the complexity of infrastructure systems and what they are and are not accomplishing. Many have illustrated the need for greater attention to knowledge infrastructure, governance, and the need for managing trade-offs. Additionally, the authors have called for greater attention to scale, context, and difference in the analysis of infrastructure systems. Critically, the contributions of this Special Issue emphasize the prevalence of power asymmetries and potential inequities in infrastructure-system development and deployment, while providing insights into analytical frameworks, tools, and concepts that can help make these inequities visible to improve decision-making for more resilient and sustainable outcomes.

We conclude by highlighting two issues that merit further work. First, the contributions here indicate that there needs to be more attention to transdisciplinary solution-based research. While there has been increased funding for such research, we argue that until graduate students are trained to work across epistemological and methodological divides, as well as to work with and communicate to nonacademic stakeholders, it is very difficult to develop truly transformative concepts and methods. Such training in transdisciplinary work is critically important in the science, technology, engineering and mathematics STEM fields that are often involved in infrastructure design, development, and implementation. Second, the research presented here indicates that there needs to be more research about the interconnections among large-scale infrastructure systems, context- specific outcomes and processes, and power and inequity in the Global South and Global North. Such research will help us to move closer to developing infrastructure systems that are more equitable and resilient.

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