Infrastructures as Socio-Eco-Technical Systems: Five Considerations for Interdisciplinary Dialogue

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DOI: 10.1061/(ASCE)IS.1943-555X.0000383

Need for Interdisciplinarity in Infrastructure Studies

Infrastructure plays a key role in 21st century sustainability challenges related to burgeoning populations, increasing material and energy demand, environmental change, and shifts in social values. Social and political controversy over infrastructure decision making will continue to intensify without robust interdisciplinary and intersectoral dialogue over national-scale and local-scale infrastructure trajectories. Alongside large investments in physical and social systems, the infrastructure community—including planners, engineers, public works specialists, financiers, and sustainability scientists—needs to articulate a 21st century vision addressing the interrelated technological, social, and environmental dimensions of infrastructure systems. Such a vision needs to address existing systems in the industrialized world and new systems in countries seeking to improve human welfare through infrastructure development.

Infrastructure systems—discussed here as primarily those integrating the built environment (Jones et al. 2001; Pulselli et al. 2007), transportation (Greene and Wegener 1997), power generation and distribution (Jacobson and Delucchi 2009), food production and processing (Food and Agriculture Organization of the United Nations 2011), manufacturing (Jovane et al. 2008), water delivery (Gleick 2003; Muller et al. 2015; Palmer et al. 2015), and waste treatment (Melosi 2008)—underpin the unprecedented material wealth of contemporary human society. These technological systems have developed alongside extensive social infrastructure including specialized knowledge and expertise housed in institutions, informal knowledge systems of operation and maintenance, and a broader system of governance and regulatory politics setting budgetary priorities, policy directions, and regulatory certainty. In combination with these policy processes, user behavior and demographic change influence the demand and maintenance costs for infrastructure services, both of which have an identified overall investment need of $3.6 trillion (ASCE 2013), $2 trillion of which is needed by 2027 (ASCE 2017). Because infrastructure relies on environmental inputs to function, channels and protects society from environmental forces, and impacts environmental systems, attitudes about technology and appropriate human–nature relationships set the goals for long-term infrastructure sustainability. They do so through both a social willingness to pay for infrastructure systems and a social consciousness of and desire for specific types of systems. Shifting environmental conditions, including climatic changes and dispersed atmospheric pollutants, are exacerbated by the *externalities* of present infrastructure systems and the technologies they support. The extent of these shifts is rarely apparent until systems become overwhelmed (Gross 2010; Perrow 1999). For example, in the case of Hurricane Sandy, siloed system management created unforeseen vulnerabilities propagating through critical infrastructure systems (Klinenberg 2013, Comes and Van de Walle 2014), serving as an example of cascading failure (Rinaldi et al. 2001), as well as affecting system restoration (Sharkey et al. 2015). At the same time, infrastructure systems and the technologies and behaviors they enable serve as sources of risks and costs to public and environmental health; 8 of 10 people now live in urban areas with excessive air pollution primarily due to transport, manufacturing, and energy generation (WHO 2016).

How has contemporary infrastructure practice come to this point? The modern infrastructure ideal of large, networked systems such as power generation, information technology, and transport (Dueñas-Osorio et al. 2007; Haimes and Jiang 2001;

J. Infrastruct. Syst., 2017, 23(4): 02517002

Winkler et al. 2011) has enabled lowered unit costs and greater accessibility while splintering social and environmental systems (Graham and Marvin 2001). In response, discourse on *appropriate technology*, emphasizing cost efficiency on both the supply side and the demand side of infrastructure thinking (Basu and Weil 1998), and work on *inverse infrastructures* examining self-organizing forms of user-generated infrastructures (Egyedi and Mehos 2012) advocate for an improved fit between technological capabilities and social goals across scales.

Current infrastructure thinking must therefore address two fundamental challenges, one physical and one social. Physically, infrastructure must continue to evolve in design, implementation, and operations and maintenance in a world changing due to the impacts of infrastructure systems and the human activities they enable. Socially, the infrastructure community must acknowledge the inherently political nature of infrastructure systems in order to overcome siloed decision-making processes around single systems. Such an understanding requires embracing the added intellectual challenge of understanding how social perception and values frame the parameters of desirable infrastructure development.

Reimagining Infrastructure as Social, Ecological, and Technological Systems

One answer to overcoming these challenges in infrastructure discourse is to catalyze broader social engagement within existing processes of infrastructure planning, design, operations, and management. Established infrastructure decision-making processes appear contained within narrow domains of expertise, subject to a large degree of physical and social inertia (Hall 2016). To foster public engagement, the infrastructure community needs to highlight the broad and cross-sectoral role infrastructure decision-making plays in escaping unsustainable development trajectories (Karlsson 2014), as well as its potential to alleviate inequality in income and access to economic opportunity, as is being taken up by numerous current policy propositions. Providing defensible analysis of those claims, however, requires a strong interdisciplinary framework capable of illuminating the interrelated dimensions of the almost invisible but necessary support systems of contemporary life (Edwards 2003).

This paper provides a conceptual framework for facilitating dialogue around infrastructural systems as irreducibly interdependent social, ecological, and technological systems (SETs). Such a complex SETs framework facilitates the integration of infrastructure knowledge and practice on two fronts. The first involves the integration of different forms of expertise, shifting the emphasis in infrastructure research away from academically siloed or specialist-led programs to one engaging the infrastructure design, implementation, management, and research communities to frame problems and solutions collaboratively. Secondly, the authors emphasize the need for better process integration, whereby design, implementation, and management processes integrate technological systems with social and ecological systems. The framework herein simultaneously allows for the interdisciplinary analysis of the (uneven) economic benefits of infrastructure development while thinking more carefully about the environmental and social impacts of infrastructure (Monstadt 2009) by expanding on the idea of *infrastructure ecosystems* (Pandit et al. 2015). The infrastructure community must acknowledge that the negative impacts of infrastructure, previously considered as externalities, have transitioned from being simply impacts on the environment, to increasingly being felt as *stresses on human systems,* including risk to life and property, increased maintenance and operations costs, declining service levels, and disruptions to social life. The community must also acknowledge that there are enormous opportunities for increasing planning and design effectiveness through a more integrated approach to reduce costs, decrease system down-time, and maximize cobenefits of joint systems operation and maintenance.

As part of thinking about the true costs and benefits of infrastructure, infrastructure systems science requires a more equitable process for articulating infrastructure's goals and design considerations. Just as the sociotechnical imaginaries of the New Deal gave rise to such examples of modernity as the Tennessee Valley Authority and the Bonneville Power Authority, the authors envision a New Green Deal, which formulates a socially equitable vision of ecological sustainability to guide technological progress (Barbier 2010; Jones and Conrad 2008). Such a vision adds to the current national dialogue on the need for large public investment in infrastructure (Infrastructure Week 2016).

This paper articulates the notion of infrastructure systems as socio-eco-technological systems, a framework entangling the social, ecological, and technological as *dimensions* of a system, rather than a series of component pieces. Dimensions must be viewed relationally, allowing the treatment of infrastructure systems as interdisciplinary objects variably constructed from differing social, ecological, and technological forces; in this sense, technologies serve as hybrids of socialized cognitive processes and the material world they inhabit. Thus SETs allow for analyzing and evaluating the impacts of different methods of analysis and system representation of infrastructure science on infrastructure governance [see Manuel-Navarrete (2015) for socioecological systems research examples]. Through such a practice these authors hope to provide a framework to simultaneously analyze the impacts of conceptual models of infrastructure systems on infrastructure decision making and engage in the infrastructure community to improve them.

Social dimensions of infrastructure comprise embedded social networks, tacit knowledge, discourses, institutions, policy, and planning in and around infrastructure systems in their imagining, implementation, and maintenance. This dimension includes the normative goal-setting processes of planning, associated analysis and apportionment of costs, risks, and benefits, and the role of regulations and subsidies in guiding technological change. Both the process and the outcomes of infrastructure planning must be equitable in order to maintain long-term involvement and to facilitate social, ecological, and financial returns on infrastructure investments.

For example, in the context of climate change, energy-intensive transportation, manufacturing, housing, and energy extraction infrastructures stemming from late-nineteenth-century inventions have created risks that threaten their continued function. Although it is tempting to view such problems as primarily technological, they are intrinsically social systems, being conceived by social actors (Jasanoff and Kim 2013), and they set the backdrop of individual social *worlds* and physical realities of *the environment*. Such a *socialization of infrastructure* through an exploration of its sociopolitical dimensions illuminates infrastructure's nature as a "total social fact" [after Marcel Mauss (1966) in Edgar and Sedgwick (1999)] because the study of infrastructure weaves together a diverse array of social lives, and the nature of infrastructure from the perspective of the individual can be used to expose the nature of society [after Bowker's infrastructural inversions (1994) in Star (1999)]. Such a perspective mirrors that of Alexander's (1977) idea of the lattice, in which interwoven and overlapping social, technological, and ecological systems combine to create the emergent urban experience. The way that people interact with infrastructure through use, operation, planning, financing, maintaining, and regulating all contribute to its manifestation as a physical phenomenon and bound the opportunities for physical system integration and decentralization (Derrible 2017). By taking these social processes into account, key operational and financial uncertainties can be exposed early on and compensated for, positively impacting longevity and functionality.

Ecological dimensions of infrastructure are composed of ecological structures (i.e., organisms, populations, communities, and ecosystems—generally networks of plants, animals, microbes, and so on), functions (i.e., primary productivity, food web interactions, carbon and nutrient cycling), and behaviors (e.g., squirrels nesting in transformer boxes, dam-building beavers) that make up, contribute to, and threaten infrastructures. Many of these ecological features and processes manifest independently of human intention, although they are enhanced or hindered by human activities and built infrastructures. This includes attempts to protect, maintain, and enhance existing and restored ecological elements providing ecosystem services, improved human well-being, urban function, and a stable global climate. Ecological networks and actors should be afforded the same consideration as social actors by being protected from harm, encouraged in their contribution to infrastructure function, and not just treated as potential sources of risk or uncertainty.

Much of the urban ecology literature has focused on humans' negative *first-order* impacts on prehuman nature (Grimm et al. 2000; McKinney 2006). This is usually understood in terms of urbanization's impact on individual organisms, and organisms' ability to inhabit urban space. Within urban ecology, scholarship has moved toward analyzing *ecology of the city*, which includes analysis of how sociopolitical processes shape urban ecosystems, rather than the previously dominant tradition of urban naturalism, which focused on the spatial patterns of plants, animals, insects, and so on, which now is referred to as *ecology in the city* (Collins et al. 2011; Grimm et al. 2000). Both ecology in the city and ecology of the city lend themselves to a valuation of urban ecosystems in terms of the ecosystem goods and services provided to humans (Gaston et al. 2013), largely focusing on health (Lee and Maheswaran 2011; Tzoulas et al. 2007), higher-order cognitive abilities (Kahn 1999), and regulation of the environmental quality and function of the urban environment via the use of green infrastructure (Amati and Taylor 2010).

Aside from explicitly using ecological processes to perform infrastructural work (as in the case of green infrastructure), infrastructure serves an ecological role in transforming possibilities for material, energy, and information flow throughout the urban system and beyond (Kennedy et al. 2007; Sahely et al. 2005). Infrastructure function also is dependent upon ecological flows operating in and around it. It is up to the infrastructure community to beneficially integrate these ecosystem processes or inevitably face them as sources of risk and operational constraint at local to global scales. Calls for infrastructure investment should internalize such ecological considerations both in terms of direct impacts on ecological patterns and processes and system-level feedback such as impacts on climate and hydrology.

Technological dimensions of infrastructure are composed of the physical technologies (e.g., hardware, steel, concrete, rebar, cable, plant, equipment, and tools) and knowledge systems (e.g., data generation and management, software, and operating instructions) of an infrastructure network, including both expert-engineered and informal work. This dimension includes the linkages between disparate infrastructure systems and their complex adaptive system nature (Rinaldi et al. 2001), therefore acknowledging the interdependent functionality of existing technological systems (e.g., necessary interactions between electricity, information technology, financial infrastructure, and mass transit). Technology and its developmental pathway cannot be seen as a value-neutral object. Rather, technology has embedded material and social consequences in terms of how it is managed, how it reshapes social life, and its inherent ecological interdependency and impacts.

Technological innovation can have direct and indirect impacts on infrastructure function, including ways of representing infrastructure systems through data, models, and media. For instance, the widespread use of GPS technology combined with advanced information systems has revolutionized understandings of commuter behavior and given rise to the *smart city* ideal (Batty et al. 2012) as well as its associated problems (Gabrys 2014). However, information technology management can only go so far in resolving on-the-ground infrastructure problems; physical design constraints provide outer limits to system adjustment, and the relationship between the two provides fertile ground for research. This relationship between macro and micro technology (Crawford and French 2008; Edwards 2003; Kemp 1994) constrains and highlights the relationship between consumer-scale technological innovation and systemic innovations in larger infrastructure systems, often by affecting user behavior, demand for infrastructure services, and avenues for service delivery and unit costs.

Five Critical Considerations Illuminated by SETs

Five critical considerations emerge from a SETs framing (Fig. 1) and provide a novel way of thinking about the infrastructure lifecycle. These are (1) setting infrastructure goals, (2) addressing complexity and scale, (3) understanding ecological-technological hybridity, (4) operating resiliently, and (5) system evolution.

These considerations are implicit in all infrastructure projects but are often taken for granted and thought to take place outside the arena of infrastructure design and management itself. A SETs framing illuminates the important role of social and ecological systems alongside technology within *all* infrastructure lifecycle stages (Fig. 2).

Democratically Setting Goals for Infrastructure Systems

Who articulates the goals of an infrastructure project? At what social and political level are goals set? What policies and regulations frame the market environment determining unit costs? Who owns infrastructure and to what purpose? How do different organizational structures affect infrastructure performance? What cultures, norms, and behaviors of the design and user communities influence

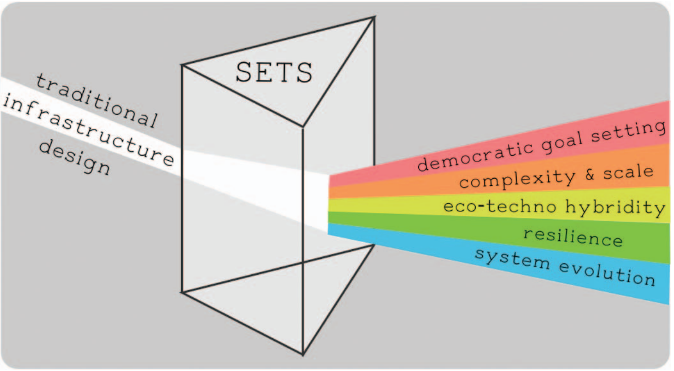

Fig. 1. (Color) SETS frame as a prism; five interdependent critical considerations can be seen when viewing infrastructure through the multifaceted lens of SETS rather than along usual, component-based disciplinary boundaries

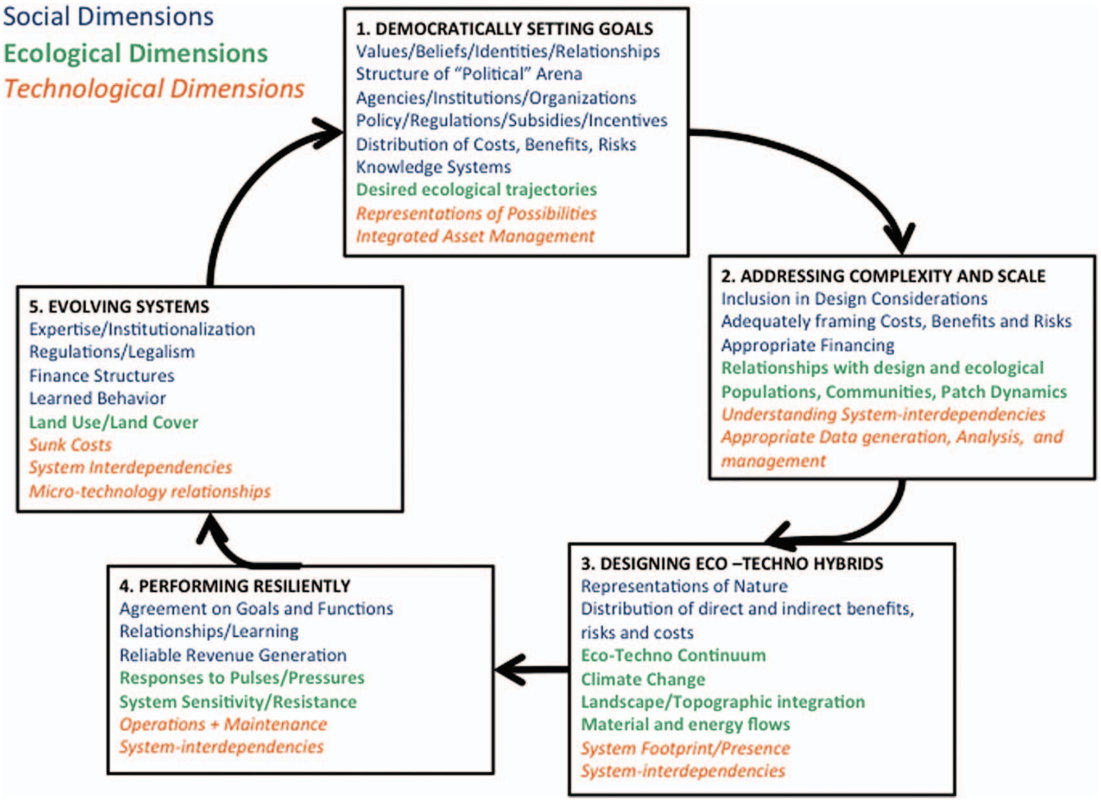

Fig. 2. (Color) Infrastructure lifecycle through the SETS prism; each consideration has several nested components relating to how infrastructure is designed, operated, and evolved

design considerations? In response to traditional technocratic planning practices, participatory-based, scenario-based, and charrette-based design and planning approaches have sought to open decision-making processes to facilitate codesign of urban environments (Innes and Booher 2010; Wates 2014).

Goals are defined as an infrastructure system's ultimate purpose, be it the provision of safe, reliable transport; clean drinking water; or dependable electricity. Goals fundamentally constrain the definition of costs, benefits, and financing of a given project and set up the trade-offs to be negotiated. They are a reflection of the *values*, *identities*, *beliefs*, and *relationships* of those at the goal-setting table. Thus, prior to any technical discussion of the efficiency of providing services, discussions need to focus on the context-specific desirability of services and options for delivering them.

Historically, large infrastructure spending programs reflected both specific political, social, and cultural projects and *collective imaginaries* that envisioned human progress as embodied in large, centralized technologies (Jasanoff and Kim 2013). The authors posit that a current shift in thinking calls for a new representation of possibilities, including both technical models and media presentations of systems that utilize technological change to preserve ecological security and integrity at local, regional, and planetary scales; it is a call to articulate desired ecological trajectories of clean air and water and resilient, biodiverse, and beautiful ecosystems vital to human well-being.

ASCE has embarked upon a promising approach to meeting these shifting demands through its *integrated systems approach*. Integrating between infrastructure systems should allow for cost savings in terms of installation and maintenance (although with increased costs during design), as in the case of dedicated bundled utility service corridors. Without such physical integration, many municipalities and nations face the challenge of attempting to create integrated asset management systems on top of spatially and administratively fractured systems (Halfawy 2008; Meite 2015; Shahata and Zayed 2010). Although such approaches represent the cutting edge of infrastructure management, their cost savings, risk reductions, and performance improvements would be much higher if the design process were similarly integrative; in both cases integration must bring together the many stakeholders needed to plan and maintain a diverse integrated system (ASCE 2009). Although the more open design process may hold the key to providing a forum for collaboration on infrastructure design, opening the process of decision making further complicates the neatness of designed solutions and requires changes to the current structure of the political arena (including bureaucracies and agencies) surrounding infrastructure design and operation.

Addressing Complexity and Scale

Infrastructure systems operate at different spatial, temporal, and social scales, and their successful implementation requires that they adequately deal with the complexity inherent in crossing scales. Most straightforwardly, crossing scales adds complexity to calculating the distribution of infrastructure effects in terms of service provision, cost recovery/revenue generation, and the apportionment of risks. Unintended consequences may accumulate downstream of infrastructure interventions, as evidenced by increased flood risk downstream of traditional flood defenses such as dikes and hardened banks (Wheater and Evans 2009). Likewise, consequences may accrue differentially over time, and subsequent generations may be harmed or reap the benefits of projects (Stirling 2010).

A SETs perspective makes apparent not only the complexities of how technological systems interact, but also how *interdependencies* between different processes at different scales can be harnessed to improve system function and lower unit costs. It becomes apparent that broad categorizations of urban form (e.g., residential, commercial, industrial, high/low density) are not particularly useful for characterizing ecological and technological relationships, even though housing types may predict coarse gradients of ecosystem service provision (Tratalos et al. 2007). Additionally, a large body of literature on how cities function as agents in global networks of infrastructure (Tranos and Gertner 2012) requires bridging global political boundaries to local levels while remaining cognizant of overprivileging the local (Jun 2013) when conceptualizing infrastructure. To deal with issues of scaling, it becomes critical to first accurately characterize drivers affecting the process at hand (e.g., climatic, landscape, and hydrogeomorphological drivers affecting flooding, stormwater management, drinking water, and/or energy provision in a complex hydraulically engineered landscape) and match the scale of the process to the scale of the intervention. Citywide modeling at superfine scales may be necessary to appropriately integrate ecological and technological systems, at least through current decision-making systems, especially as predetermined topographic/geomorphic boundaries are not necessarily relevant to many ecological processes (Post et al. 2007).

Lastly, different disciplines and sectors have different foci on very different spatial, temporal, and social scales. Acknowledging scale dependency of different analytical frameworks will be required to address those types of scale incompatibilities. The generation of knowledge academically as well as operationally around infrastructure must take scale dependencies into account when generating data, as well as analyzing operations, maintenance, and management.

Designing Ecological-Technological Hybrids

The *ecological-technological* hybridity of urban infrastructures highlights the interdependency of ecosystems and built infrastructures. All human-built infrastructure is embedded in an ecological system; ecology and earth systems form the background, base parameters, and many of the component pieces of the services provided by infrastructure (Carse 2012; Edwards 2003). During the design process, particular representations of natural processes become fixed in design criteria, including metaphysical ideas about how nature works [e.g., resilience, frailty (Gunderson and Holling 2002)] and technically constructed models of biophysical processes, such as climate change projections. Careful attention must be paid to the actual representativeness of these social and technical constructs in order to adequately design systems.

From a purely ecology-based approach to infrastructure, humans simply act as another *ecological engineer* (Smith 2007), capable of transforming their physical habitat for their benefit in ways that impose, improve, and worsen conditions for other members of the ecological community. Research on urban metabolism (Kennedy et al. 2007; Pincetl et al. 2012; Wolman 1965) and industrial ecology (Erkman 1997) function to analyze and optimize industrial material, energy, and information flows at the landscape scale. Through the combination of these perspectives, infrastructures act as the multifunctional and redundant systems of a robust hybrid techno-ecosystem designed and operated by multiple ecological actors. As evidenced by emergent urban ecosystem services research (Millennium Ecosystem Assessment 2005; Potschin and Haines-Young 2011), green infrastructure designs intend to produce multiple benefits; however, benefit provision depends on where a facility falls along the ecological-technological continuum [see Royal Society (2014) for a similar treatment]. Explicitly analyzing the connections and interdependencies along an *eco-techno continuum* between technological and ecological systems transcends existing ways of thinking about the impacts of infrastructure decision-making just based on system footprints.

Such a multibenefit approach is illuminated by a SETs framing in which social and technical successes are inextricably linked to ecological function. For example, many cities already pursue joint strategies of improved stormwater management by increasing conveyance capacity through traditional grey infrastructure and reducing runoff rates to combined sewer systems by using distributed green infrastructure, such as Portland, Oregon, Philadelphia, and New York City. Green and grey facility types require different maintenance regimes (i.e., plants are managed differently than pipes), requiring different kinds of expertise at the local management level (Carlet 2015). However, if integrated wisely, such hybrid gray-green systems can provide functional certainty as well as cobenefits including ameliorating urban heat islands (Emmanuel and Loconsole 2015), improving air quality of indoor environments (Wang et al. 2014), enhancing the visual and recreational quality of development (Nazir et al. 2014), and contributing to urban renewal and city competitiveness (Bennett 2013; Philadelphia Water Department 2011). However, as with all infrastructure interventions, there exist inherent social conflicts over appropriate methods and consequences of urban renewal (Lubitow and Miller 2013).

Debate continues over such soft path versus hard path approaches toward infrastructure planning (e.g., Gleick 2003; Palmer et al. 2015; Muller et al. 2015); acknowledging hybridity in all approaches can resolve this debate by focusing instead on an appropriate degree of hybridity for the task at hand. Significant consensus on the value of ecosystems' infrastructural work has already created substantial policy instruments, such as the Water Resources Reform and Development Act of 2013. Ultimately, infrastructure systems evolve alongside and in relation to their resident ecologies; design should be flexible enough to anticipate change and robust enough to deliver under uncertainty.

Performing Resiliently

Traditional infrastructures are designed to operate reliably to reach the agreed upon goals and functions of the system, often in a failsafe manner (Ahern 2011), and their resilience is often defined by their ability to continue to operate under surprise shocks (Rogers et al. 2012) or their ability to recover quickly and adapt to changing circumstances through networked architecture reinforcing learning behavior (Woods 2015). However, mounting challenges specifically related to climate change create *wicked problems*, defined by irreconcilable problem framings (Rittel and Webber 1973), manifest in disagreement over the relative desirability of using infrastructure to adapt to or to mitigate the impacts of climate change. While technical and political blocs argue over solutions, climatic conditions continue to shift with increasing variability exceeding known conditions (Seager et al. 2012), making fail-safe systems increasingly difficult to design and maintain.

With the advent of unpredictable hazards, a growing body of engineering literature attempts to move from the traditional approach of risk management toward an ecological-resilience approach within a systems-engineering framework, explicitly including the value of *social learning and knowledge*. Such an approach refers to an infrastructure systems' social, ecological, and technological ability to recognize and absorb variation, disturbances, and surprises (Hollnagel et al. 2007), often through adaptive management (Linkov et al. 2013). Systems approaches to resilience engineering embrace system dynamics (Fiksel 2003) and evolve systems through a constant cycle of anticipation, monitoring, and adaptation (Seager et al. 2012; Woods 2015).

These approaches can draw upon strategies developed by Ahern (2011) to integrate ecological interdependencies for enhancing resilience capacity; for example, redundancy—having multiple infrastructure components that could provide the same service in case of failure of one component. Although traditionally this has been seen as inefficient in optimized engineered systems (Park et al. 2013), integrated planning identifies a desirable level of redundancy for a system to continue to function when disturbed (Mitra et al. 2010). The strategy of multifunctionality in resilient infrastructural systems (Ahern 2011) can be leveraged using the notion of ecological-technological hybridity. Thus, multifunctional infrastructure can allow a smaller amount of space and funds to provide the same benefits as multiple single-function infrastructures. For example, in the city of Rotterdam, spaces have been designed to be multifunctional: parks and basketball courts most of the time can serve as water storage facilities in times of flooding (Klinenberg 2013; Shorto 2014).

Alongside this sensitivity and resistance to pulses and pressures of physical systems, a key component of resilience is a system's social infrastructure, or the ways in which operators generate and share knowledge and experience through their networked relationships (often in unanticipated ways) to maintain function and minimize damage under extreme stress, as well as recover after extreme events (Aldrich and Meyer 2015) and more generally in day-to-day operations and maintenance (O+M). Previous disasters like the Chicago heat wave of 1995 and Hurricane Sandy in 2013 highlight the importance of social capital and community networks in preventing mass casualties. Extending the notion of social infrastructure beyond the confines of a single system, it becomes apparent that overall system resilience also requires sustainable economic connections and financing. Systems recoup costs either through revenue generation or through public expenditures requiring highly politicized financial administration, either of which critically determines design parameters and O+M budgets. System resilience cannot be defined in isolation of how the system *lives* socially; adaption to change requires intelligent behavior before, during, and after its design phase, as well as a public that experiences its benefits as equitable rather than contributing to economic and social inequalities (Fernández et al. 2016).

An excessive focus on resilience, in all four senses of the word [system rebound, robustness, extensibility, and adaptability (Woods 2015)], neglects the more pressing need facing infrastructure systems—that of evolving the system. Such a consideration goes beyond emerging joint frameworks for analyzing sustainability and resilience, which certainly address numerous considerations articulated within this paper (Bocchini et al. 2014). However, it has become clear that infrastructure systems, and the sociopolitical relations that have produced them, are becoming primary drivers of risk generation to those systems, risks that continue to intensify the more the current system architecture is maintained, enhanced, and defended. Such a claim will likely make many within the current infrastructure community of practice uncomfortable. However, in an era of intensifying climate change, rising economic and political inequality, and clamoring demand for new services and economic structures, the infrastructure community cannot continue to defend outmoded, increasingly obsolete and maladaptive forms of infrastructure planning, design, and governance. Efforts will be better spent thinking creatively about how to evolve.

Evolving Systems

The last stage in this framework pertains to infrastructure systems' evolution, which critically must overcome constraints on innovation. In theory, it would be quite easy to utilize current calls for infrastructure investment to significantly improve and redesign existing infrastructure systems. However, in the existing planning and policy environment, legal, regulatory, and institutional structures have privileged particular forms of expertise and created both physical and intellectual path dependencies via sunk costs in social and technological infrastructures. Often, political and financial decision makers choose to make incremental fixes to existing systems in the face of knowledge that incremental fixes are inadequate (Hommels 2005). In this sense, a financial path dependency occurs, where obdurate modes of infrastructure spending accumulate costs over time, neglecting spending on preventative measures and locking-in undesirable trajectories (Kong and Frangopol 2003). Obduracy refers to the inability to evolve a system despite recognized need for change and, less dramatically, constrains the directions in which the system can evolve despite recognition of new goals and design considerations. When designing infrastructure systems of the future, planned obsolescence may be a key yet underappreciated component of infrastructural evolution (Lemer 1996). Modular and appropriately scaled systems that meet the demands of shifting demographics (Ansar and Pohlers 2014), overcoming routinized learned behavior (Star 1999), and adapting to changing environments (Infrastructure Climate Change Impacts: Report Card 2015) may prove to be even more effective.

With the advent of regulation of waste disposal practices [a social and economic decision with technological consequences (Melosi 1990)], many cities in the United States were historically forced to confront the challenge of no longer discharging untreated sewage into open water bodies using combined sewer infrastructure. Many opted to channel both storm and sanitary systems to centralized wastewater treatment plants before discharge. However, changes in storm frequencies and continued population growth has overwhelmed the capacity of these combined systems, causing major ongoing water quality and public health issues. Due to the perceived high cost of separating combined sewer systems, most municipalities opt to maintain the existing pipe network (EPA 2004), and increase capacity by increasing the size of central conveyance arteries and treatment plants, as in the case of Portland, Oregon's *Big Pipe* project, and in the current London Thames Tideway Tunnel Projects. Although often touted as cheaper than separating systems, such centralized projects incur enormous long-term costs associated with financing and miss opportunities to derive additional services from systemwide improvements. These systems continue to face large uncertainties in future performance requirements due to changing flooding frequencies around the continental United States (Melillo et al. 2014), exacerbated by increased runoff rates from ongoing land use (Grimm et al. 2008), and further complicated in coastal regions by rising sea levels (Hallegatte et al. 2013).

These factors highlight the interplay between the complexity of anticipating multiscalar changes in system parameters and socially negotiating desirable developmental pathways. Broader patterns of land use and urban development affect infrastructure pathways in more ways than stormwater volume increases; patterns of built environment development fundamentally define infrastructure needs and costs by defining service density and demand. Thus, urban and spatial planning should ideally be utilized to coordinate long-term development trajectories with infrastructure needs as an explicit part of the planning calculus.

Overcoming physical path dependencies and cost barriers, large-scale infrastructure integration and evolution faces the challenge of bringing together managers and agencies across a range of disciplines and overcoming barriers to public engagement. Traditionally, specific agencies with relevant expertise managed particular types of infrastructure at politically determined scales, e.g., municipal, state, or federal levels. Bridging existing silos requires coordination of conflicting perspectives and expertise as well as diverse funding sources and budget allocations. The ASCE has identified interdisciplinary coordination as a key to infrastructure planning and management and has stated that the failure to share knowledge across agencies can compromise the system's ability to properly function under extreme events (ASCE 2009). On the municipal level, New York City provides one example of successful interdepartment coordination for infrastructure management: the New York City Department of Parks and Recreation, Department of Environmental Protection (DEP), and Department of Transportation (DOT) have forged a coordinated effort to implement bioretention swales in city sidewalks that will manage stormwater runoff in addition to providing cobenefits like pollinator habitat and shade (NYC DEP 2013). On the federal level, the U.S. Department of Housing and Urban Development (HUD), DOT, and EPA have formed a partnership to coordinate housing and transportation development in pursuit of creating more sustainable communities (EPA 2014). However, agency coordination without public engagement around qualitatively different goals will not evolve systems.

New Directions for Infrastructure Systems

Achieving sustainable, integrated infrastructural systems requires an interdisciplinary research approach that bridges the silos of different expertise, forms of governance, and social worlds (Lave et al. 2014). The infrastructure community will also need to work across spatial, temporal and organizational scales: microscopic to global, seconds to centuries, species to ecosystems, town halls to Congress and beyond.

Overall, the authors hope to invigorate research and dialogue around infrastructure systems in order to guide investments that wisely integrate into ecosystems, provide for improved social wellbeing, and utilize the best technical knowledge. The real test for this framing will be its application in live infrastructure planning processes open to public and expert participation. Such a framework lends itself readily to analysis of both opportunities to improve the effective management and investments in existing infrastructure systems, as well as providing a platform for thinking about how to evolve infrastructure systems to meet a wider variety of socially conscious and environmentally friendly goals while providing for human well being. The authors hope a stimulated interdisciplinary discussion will help the infrastructure community collectively envision new infrastructure ideal, sustainably utilizing humans' vast transformational capabilities to better the human condition while improving relations with the rest of life on earth.

Acknowledgments

The authors would like to thank the organizers of the Third National Conference for Sustainability IGERTs held in September 2013 at Portland State University which hosted the workshop that led to the creation of this paper. This work was supported by numerous grants from the National Science Foundation, including the Graduate Research Fellowship Program under Grant #DGE-1057604 and 1069193; the NSF-IGERT Program under Portland State University's Sustaining Ecosystem Services to Support Rapidly Urbanizing Regions, Grant #0966376; the Cornell Cross-Scale Biogeochemistry and Climate IGERT, Grant #DGE-1069193; the University of Pittsburgh Sustainability Initiative in Engineering IGERT, Grant #DGE-050434; the Columbia University Solving Urbanization Challenges by Design IGERT, Grant #DGE-0903597; and the University of Alaska, Fairbanks Global-Local Interactions: Resilience and Adaption of Social-Ecological Systems in a Rapidly Changing North, Grant #DGE-0654441. Z. Grabowski and A. M. Matsler would also like to acknowledge the support of Portland State University's Institute for Sustainable Solutions and the Miller Foundation Award. The authors also would like to acknowledge the editor and three anonymous reviewers for comments and stimulating critiques which greatly improving the clarity and quality of the manuscript.

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