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Title

Lock-in: Origination and Significance within Infrastructure Systems

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ABSTRACT

Infrastructure systems have legacies that continue to define their priorities, goals, flexibility, and ability to make sense of their environments. These legacies may or may not align with future needs, but regardless of alignment, they may restrict viable pathways forward. Infrastructure ‘lock-in’ has not been sufficiently confronted in infrastructure systems. Lock-in can loosely be interpreted as internal and external pressures that constrain a system, and it encourages self-reinforcing feedback where the system becomes resistant to change. By acknowledging and recognizing that lock-in exists at small and large scales, perpetuated by individuals, organizations, and institutions, infrastructure managers can critically reflect upon biases, assumptions, and decision-making approaches. This article describes six distinct domains of lock-in: technological, social, economic, individual, institutional, and epistemic. Following this description, strategies for unlocking lock-in, broadly and by domain, are explored before being contextualized to infrastructure systems. Ultimately, infrastructure managers must make a decision between a locked in and faltering but familiar system or a changing and responsive but unfamiliar system, where both are, inevitably, accepting higher levels of risk than typically accustomed.

1 INTRODUCTION

Infrastructure systems have legacies that continue to define their priorities, goals, flexibility, and ability to make sense of their environments. Most infrastructure managers (engineers, architects, construction workers, and other practitioners in governmental organizations, consultancies, and private industry who plan, design, build, operate, maintain, and decommission infrastructure systems) today have inherited systems designed to confront simplified conditions and challenges (e.g., a predictable rather than unpredictable climate, or new builds versus retrofitting) (Olsen, 2015; Sovacool et al., 2018; Elmqvist et al., 2019; Helmrich & Chester, 2020; Underwood et al., 2020; Markolf et al., 2020; Sovacool et al., 2020; Chester et al., 2021); therefore, infrastructure reflect a narrow set of past objectives and assume relatively stable environmental conditions. This legacy places infrastructure systems on a trajectory that is increasingly decoupled from the growing complexity of today's and future environments (Chester & Allenby, 2022), and perpetuates inflexibility in infrastructure design (Chester & Allenby, 2018; 2019). This decoupling leads to infrastructure systems that are increasingly incapable of responding to new, temporary equilibriums as well as shock events. Due to gradual change and short-term objectives (e.g., maintaining low costs), it can be difficult to identify the entrapment of an obdurate system, or a system defined by its legacies rather than its potential to meet future demands. Legacies, as used here, are broadly representative of the long-lasting impacts of past decisions related to the physical and/or governing structures of infrastructure systems. Infrastructure systems must be able to manage their legacies in order to effectively respond to the diverse challenges of the Anthropocene.

Infrastructure systems consist of physical networks and governing institutions that impact the ability of the system to be responsive to emergent changes, i.e., flexible. The decisions made within infrastructure systems also have rippling effects for systems coupled with infrastructure (e.g., health care, supply chains) and vice versa, indicating the design space of infrastructure is much broader than design and management within the infrastructure itself. Honing in on design choices within infrastructure, physical networks constrain future decisions through two primary factors: 1) sunk costs (e.g., money, space) where resources are already invested (and continue to be invested) in the current system, making it difficult to divert resources to another potential configuration and 2) technological interrelatedness, meaning significant changes in one sector will have cascading impacts on other sectors that will subsequently need to make modifications (Reyna & Chester, 2014; Chester & Allenby, 2018). The institutions surrounding infrastructure also restrict design choices through legal and political factors such as performance goals, financing, organizational culture, and legal requirements, which are oftentimes put in place for safety (Cairns, 2014). Social norms and expectations place pressure on infrastructure systems – communities have implicit and explicit expectations about the availability, quality, and reliability of provided goods and services (Shove, 2003).

Both the physical and institutional components of infrastructure systems continue to emphasize armoring, strengthening, hardening, and low-regret strategies to avoid failure and meet societal

expectations (Woods, 2015; Helmrich & Chester, 2020). Robustness-centric approaches create infrastructure that can withstand more disruptions (either in variety or in magnitude) but are still inflexible, as the approaches are anticipatory and controlling rather than adaptive to changing conditions (Anderies et al., 2013; Woods, 2015; Galaitsi et al., 2021). Robustness is oftentimes conflated with resilience in engineered systems, meaning institutions will engage robustness strategies as resilience strategies, but it is only one component (Woods, 2015; Yodo & Wang, 2016; Helmrich et al., 2020). For instance, an infrastructure manager may decide to design a structure to withstand RCP6.0 to accommodate minor to major impacts from climate change, but this may be over- or under-designing to future conditions. As environmental conditions accelerate, becoming increasingly uncertain and more complex, robustness strategies alone will not be sufficient, and infrastructure managers will need to transition physical networks, governing institutions, and educational practices while operating within the confines they wish to transcend. It is critical to understand why infrastructure systems remain on rigid paths in order to realign to more flexible trajectories (Chester & Allenby, 2019).

To understand legacies and the resulting effects on the trajectories of infrastructure systems, it is useful to examine the choices that were made when infrastructure systems were implemented. Exploring decision-making and design goals can be difficult, Kanoi et al. (2022) provide four discussion points to further understanding of design choices: underlying presumptions, target audiences, expected usage, and impacts. By probing design choices, insights can be gleaned about the decisions being made by infrastructure managers and their potential for long-lasting impacts. For instance, consider if an infrastructure manager designing a system frames the goal as either the provision of specific resources for services (e.g., electricity for heating and cooling) or the facilitation of enabling human capabilities (e.g., maintaining good health). As long as infrastructure systems presume the former, it will be difficult to develop the necessary flexibility and agility to respond to changing environments; therefore, infrastructure managers should evaluate presumptions and biases during the design process. By framing infrastructure systems as enabling human capabilities, people are clearly intertwined with infrastructure systems. This identifies that infrastructure systems are fundamentally social structures built for the people – not ‘simply’ technological systems built to transform and transport resources. When infrastructure is framed as a technological resource, it is easier to fixate on the reliability of providing that resource rather than the quality of services (Allenby & Chester, 2018; Clark et al., 2018; Carvalhaes et al., 2020; Kanoi et al., 2022). Thus, the initial goal framing impacts the identification of who infrastructure systems are built for, which impacts the intended utility. Infrastructure systems are perceived as responsible for provisioning basic rights such as access to clean water, or more recently, Wi-Fi; however, the perception of whether infrastructure systems are social, public, or private – or a combination – goods vary (Proag, 2021). Further, considering the impacts, infrastructure systems shape social relations, as seen through equity and social justice outcomes (Clark et al., 2018; Kanoi et al., 2022). The quality of infrastructure services can vary by location (Clark et al., 2018), and many infrastructure structures disproportionately impact those in close

proximity negatively. Navigating through the four prompts (presumptions, target audience, expected usage, and impacts) allows infrastructure managers to examine design choices and recognize how these choices begin to influence the trajectories of their systems.

Ultimately, there appears to be a socio-technical trajectory – inherited from the legacies of previous decisions – that infrastructure systems are constrained within. This ‘lock-in’ can loosely be interpreted as internal and external pressures (e.g., sunk costs and social norms, respectively) that constrain a system, and it encourages self-reinforcing feedback where the system becomes resistant to change (Arthur, 1989; Cecere et al., 2014). Historically, infrastructure systems have not been designed with the agility and flexibility to be more responsive to shifting goals and conditions (Chester & Allenby, 2018). As a result, they are not able to address lock-in and create viable pathways forward. In the Anthropocene, infrastructure will need to be flexible to respond to increasing interconnectedness and growing complexity, and lock-in may be inimical to adaptation and transformation. Despite these concerns, theory for why infrastructure systems remain on restrictive trajectories appears to be limited, and given the increasing interest to make infrastructure resilient, adapted, and transformed, it is necessary to first understand and address the forces that constrain change. Hetemi, Jerbrant, & Mere (2020) state that “lock-in has been contemplated either as a starting point or an outcome, but the process logic that gives rise or supports it remains underexplored” in regards to large-scale projects. As such, an examination of infrastructure lock-in, what it is, how it’s defined, and what it means is necessary. In Section 2, the historical use of the term lock-in, including a catalog of lock-in domains, is established. Section 3 identifies mechanisms to ‘unlock’ infrastructure systems, and Section 4 discusses current strategies for unlocking infrastructure systems. Lastly, Section 5 provides a brief conclusion.

2 HISTORICAL ANALYSIS OF LOCK-IN

The phrase lock-in largely appears in literature regarding technology, infrastructure, and carbon. Generally, lock-in is the entrenchment of a technology due to an initial context that favors the adoption, continued investment into a technology, and, lastly, increasing returns that reinforce the technology and diminish opportunities for other technologies. More specifically, lock-in, as quoted from Cecere et al. (2014) and aligned with many other academics, occurs when “returns of adoption cause a pathway to become self-reinforcing” (Arthur, 1989; Pierson, 2000; van der Vleuten & Raven, 2006; Cantarelli et al., 2010; Khalil, 2013; Klitkou et al., 2015; Heeres et al., 2015; Seto et al., 2016; Wesseling & van der Vooren, 2017; Hetemi et al., 2020). A few take this definition further, stating that lock-in occurs when the implemented solution is inefficient compared to other available technology, or the implemented technology has significant negative consequences (Cantarelli et al., 2010; Corvellec et al., 2013; Cairns, 2014; Markolf et al., 2018). However, lock-in is at times necessary to create opportunities for technology development (Cantarelli et al., 2010; Cairns, 2014; Klitkou et al., 2015; Goldstein et al., 2023) or ensure compatibility between interconnected systems (e.g., computer design and software). Lock-in

cannot be simplified to an end-state, but rather it is a process that leads to reliance on a particular technology. This process must be accepted and managed, rather than ignored or eliminated.

The concept of lock-in emerges under various pseudonyms in infrastructure literature. Hughes (1983) is oftentimes accredited within infrastructure literature, despite not explicitly using the term. He stated that large technical systems are not independent of their context. The concept of lock-in emerges under related terms such as structural inertia and imprinting (organizational theory), social traps, reverse salient, entrapment, and entrenchment (Hughes, 1983; Costanza, 1987; Arthur, 1989; Hannan & Freeman, 1989; Walker, 2000; Cantarelli et al., 2010; Cairns, 2014; Cecere et al., 2014). And, frequently, lock-in is discussed through an antithesis: transformations. Transformations are non-linear changes or radical shifts away from business as usual (Pelling et al., 2015). Transformations are driven by shocks and stressors, which serve as incentives for change (Wilson, 2013; Khalil, 2013), and can occur through leverage points (e.g., organizational structure, system goals, collective cognition) (Meadows, 1999). Lock-in directly challenges efforts of transformation as it forces systems to remain on a specific path.

There are many contributing factors to systemic lock-in. Lock-in is most commonly associated with technological and institutional components, but lock-in can also be imposed by consumers (e.g., resistance, cost of learning, social context) (Foxon, 2002; Cecere et al., 2014). Lock-in can occur due to learning effects, economies of scale, economies of scope, network externalities, informational increasing returns, technological interrelatedness, collective action, institutional learning effects, and differentiation of power and institutions (Klitkou et al., 2015). Lock-in is particularly difficult to address because it occurs outside the scope of risk and capacity approaches (Payo et al., 2016). Risk-based approaches identify a recommended size of infrastructure for a particular hazard as expected costs (Lewis, 1992), but many consequences are difficult to quantify into costs (Markolf et al., 2020). Relying upon quantitative metrics, and ignoring qualitative metrics, can lead to prematurely committing to a technological solution (e.g., armoring infrastructure), resulting in lock-in. Capacity approaches, found in adaptation planning, examine existing capacities and vulnerabilities within a system to identify low-regret solutions, or solutions that address a range of potential futures (Vermeulen et al., 2013). Capacity approaches favor incremental change, which can still lead to lock-in if there is a lack of vision. Furthermore, the lock-in of one infrastructure system does not remain isolated due to the interconnectedness of the infrastructure sectors (i.e., coevolution) so there is an interplay of interdependence, joint-use, and competition (Frantzeskaki & Loorbach, 2010).

Lock-in is a driver of *path dependence* (Leibowitz & Margolis, 1995; Page, 2006; Cairns, 2014). With the lack of competition and continued commitment to a chosen technology, path dependence can occur (Arthur, 1989; Khalil, 2013). Infrastructure literature tends to muddle the definitions and relationships between lock-in and path dependence. Path dependence is defined as when “important influences upon the eventual outcome can be exerted by temporally remote events,

including happenings dominated by chance elements rather than systematic force” (David, 1985). This definition arose from the observation of technologies becoming entrenched despite inefficiencies (e.g., the QWERTY keyboard layout (David, 1985), or railway track gauges (Puffert, 2002)). Leibowitz and Margolis (1995) identify three degrees of path dependence: 1) sensitivity to starting parameters but no implied inefficiency; 2) sensitive dependence on initial conditions leads to outcomes that are regrettable and costly to change; and 3) sensitive dependence on initial conditions leads to an outcome that is inefficient but remediable.

Infrastructure managers create third-degree path dependence when they default to the status quo – whether intentional or unintentional – when there is a less regrettable trajectory (e.g., emergent technology or new funding policy). Khalil (2013) asserts that there are two reasons individuals fall back on default positions when making decisions: omission bias and procedural rationality. Omission bias is when a decision-maker feels less pain from a failure due to the result of *not* fixing something (e.g., technical component, institution, norm), and they would experience more pain if they attempted to institute a fix, but failure still occurred. This bias can drive decision-makers to adhere to the status quo rather than experiment with new ideas (Kahneman et al., 1982; Baron, 2000; Khalil, 2013). Procedural rationality asserts that humans are creatures of habit, so they choose a technology that has proven to work even if it is not the best available solution (Simon, 1976; Khalil, 2013). While maintaining an infrastructure system the manager may decide that the operations are sufficient to meet needs for *today*, rather than considering how those needs are changing over time, since the minimum requirement is being met. This can result in shock events being major drivers of change as the organization acknowledges its failures to respond to current conditions corresponding with a window of opportunity to change (Khalil, 2013; Abson et al., 2017; Iwaniec et al., 2019; Monstadt et al., 2022). However, it is critical to keep in mind the spatial and temporal scales when making these decisions to ensure that the entire system is not optimized for a temporary state (Chester & Allenby, 2019; Helmrich & Chester, 2020). This is a complicated task, as decisions are made across a wide array of domains (e.g., economic, institutional, technological), which each have unique pressures and consequences in varying contexts (e.g., water vs. power infrastructure, short- vs. long-term planning, etc.). The following sub-section catalogs how lock-in specifically emerges across domains so that infrastructure managers may identify lock-in within their systems.

2.1 Catalog of Lock-in Domains

While the outcome of lock-in is generally agreed upon, the application of the term is inconsistent in the literature on infrastructure systems. Sixteen different domains of lock-in emerged in the reviewed literature. Many of these domains were not distinct, but – even amongst the distinct ones – not every domain was identified by each article. Table 1 presents a catalog of distinct lock-in domains along with a synthesized definition, contributing conditions from key articles, and an example. The domains are categorized by the scale of influence: micro, meso, or macro. While resilience operates on a macroscale and engineers often on a microscale (Helmrich and Chester,

2020), infrastructure systems bridge scales (Edwards, 2002). The microscale represents the minimum unit to influence design while the macroscale represents the maximum. For instance, epistemic lock-in influences individual and organizational sensemaking, leading this domain to have a broader, top-down (systemic) impact. Meanwhile, an individual may perpetuate lock-in from the bottom up, demonstrating the microscale. The mesoscale is representative of intermediate units of influence. Further, nested domains, or domains that are embedded together, are marked with an asterisk; i.e., the individual, institutional, epistemic spectrum. This framing is explored more closely in Section 3, after the introduction of domains. The diversity of domains illuminates the number of decision spaces that can have long-lasting impacts on infrastructure systems and prevent transitions toward more resilient infrastructure.

Table 1. Catalog of Lock-In Definitions and Contributing Conditions by Domain

Domain	Definitions and Contributing Conditions
Microscale	
Individual (including psychological)*	<i>Lock-in caused by experience, familiarity, status quo, or routine, along with a reliance on stationarity.</i> • concepts of planning fallacy and optimism bias (Flyvbjerg et al., 2003; Cantarelli et al., 2010) Example: Large infrastructure projects are considered a technological problem resulting in technological solutions, which discounts alternatives (Flyvbjerg et al., 2003). This can be perpetuated at the individual, institutional, or epistemic scale (hence, these scales are nested).
Mesoscale	
Institutional (including political and functional)*	<i>Lock-in caused by formal and informal governance – frequently by intentional design and/or by vested interests and stakeholders (from individuals to corporations to governments) that are typically financially motivated.</i> • structuring of institutional activities to fulfill socio-economic purposes (Foxon, 2002) • legal and political dimensions (Corvellec et al., 2013) • intentional feature of institutional design to reinforce status quo trajectories or create and stabilize a new status quo (Seto et al., 2016) • deliberate and strategic underestimation of costs when forecasting outcomes (Flyvbjerg et al., 2003; Cantarelli et al., 2010) • through professional associations or coalitions of industrialists and politicians (Grabher, 1993; Corvellec et al., 2013) • through joint-investments or personal ties (Grabher, 1993; Corvellec et al., 2013)

	Example: Stakeholders benefit from the existence of an infrastructure (e.g., conventional energy infrastructure) and, therefore, advocate for policies and rules to protect that interest (e.g., remove tax credit for solar energy infrastructure) (Seto et al., 2016).
Technological (including infrastructural and structural)	<i>Lock-in caused by the adoption of a particular technology that becomes entrenched due to familiarity and economic advantages.</i> • extent to which such factors favor incumbent (Foxon, 2002) • technologies against newcomers (Seto et al., 2016) • long lifespan of physical infrastructure (Flyvbjerg et al., 2003; Cantarelli et al., 2010; Seto et al., 2016) • 'forecasting errors' expressed in technical terms (Flyvbjerg et al., 2003; Cantarelli et al., 2010) • economic advantages (Corvellec et al., 2013; Seto et al., 2016) • infrastructure interdependence (Corvellec et al., 2013) • embeddedness of communities within transport, food and energy networks, or the geographical location of a community with associated constraints and opportunities for economic development (Wilson, 2013) Example: Pursuing a familiar technology (e.g., railroads in the case of the Betuweroute project) rather than seeking alternatives (Cantarelli et al., 2010).
Social (including cognitive, socio- psychological, behavioral, and cultural)	<i>Lock-in caused by personal or collective understandings based on previous experiences (e.g., cultural and societal norms).</i> • common ways of interpreting or envisioning (Grabher, 1993; Corvellec et al., 2013) • community-level endogenous social and psychological factors (Wilson, 2013) • lifestyles, behavior transitions, habits (Seto et al., 2016) • public support, success story (Corvellec et al., 2013) • societal moral codes, traditions, religion and rites, the general political orientation of a community, and other moral and behavioral codes (Wilson, 2013) Example: Culture may restrict changes to infrastructure, as seen with Amish communities in the US whose religious beliefs restrict the use of electricity (Wilson, 2013).
Macroscale	
Epistemic (including	<i>Lock-in caused by scope and legitimacy of knowledge-making practices and concepts.</i>

educational)*	• listed, but not defined, by Cairns (2014) • scope, diversity and legitimacy of a variety of knowledge-making practices and how they shape decisions (Muñoz-Erickson et al., 2017; Miller et al., 2018) Example: With infrastructure systems being increasingly entangled with digital technologies, infrastructure managers must be trained in cybersecurity; however, this is not reflected in the US educational system (Allenby & Chester, 2018).
Economic	<i>Lock-in caused by capital investments and recurring costs, typically of technological components but also social and ecological components, as well as subsidies, taxes, penalties, etc. that impact profitability.</i> • issues of either economic self-interest or public interest (Flyvbjerg et al., 2003; Cantarelli et al., 2010) • the impact of globalization and capitalism on community resilience (Wilson, 2013) Example: The HSL-Zuid (i.e., High-speed Line South) project was restricted by stringent budgeting control (in response to potential cost overruns) that limited options regarding risks, scope, design, and quality of contracts (Cantarelli et al., 2010).

*nested

The six domains can influence infrastructure systems on different temporal and spatial scales, depending on the decision-making occurring within them. To further confound matters, these domains are interconnected. For instance, formal governance of infrastructure systems may restrict the amount of economic resources that can be used on a project. Therefore, the interactions between existing technology, policies, norms, resources (e.g., time, space, money) can further perpetuate lock-in due to increasing returns, making it difficult to adapt or transform in response to the changing environment (van der Vleuten & Raven, 2006; Chester & Allenby, 2019). The interplay of these domains is conceptualized in Figure 1, where the solution space for infrastructure systems is becoming increasingly constrained. It is critical to recognize the role each of these domains places on infrastructure systems rather than focusing on one particular domain. This may require a change in perspective as infrastructure are frequently reduced to their technological components, despite the significant role of institutions and governance (social components) (Foxon, 2002; Seto et al., 2016; Helmrich and Chester, 2022) and natural (or ecological) infrastructure (Markolf et al., 2018; Matsler et al., 2021). In brief, infrastructure systems are socio-technical, resulting from the physical assets (natural or built) and from the institutions that govern the systems, and they are impacted by social, ecological, and technological environments that are evolving more quickly than infrastructure systems.

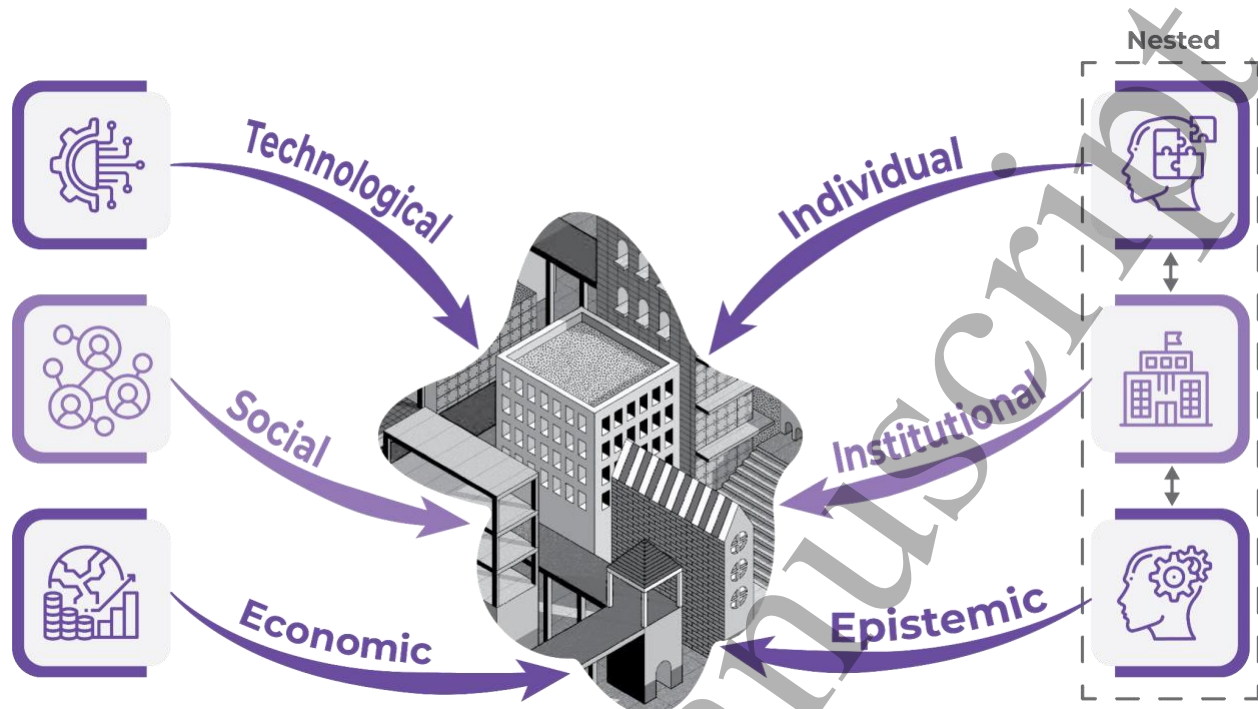


Figure 1. Lock-in domains (purple arrows) constrain the solution space (amorphous grey area) of infrastructure systems, making it difficult for these systems to respond to growing complexity.

The context will determine the strength of each lock-in domain on the system.

The intractability of coupled constraints can make it difficult not only to diverge from the current path but to identify which force(s) are most critically influencing the system, and whether that influence is at a decision-making or project level (Cantarelli et al., 2010). Further, lock-in domains are not always independent of one another but can co-evolve, reinforcing or weakening influences amongst the domains (Foxon, 2002; Corvellec, 2013; Klitkou et al., 2015; Seto et al., 2016). This intractability has been observed in literature surrounding carbon lock-in, where “existing technologies, institutions, and behavioral norms together act to constrain the rate and magnitude of carbon emissions reductions in the coming decades” (Seto et al., 2016). Urban systems rely upon carbon-intensive energy infrastructure, but fossil fuels – the majority of energy sources – are limited and impact people and the environment. This leads to the question, Why are urban systems reliant on carbon-emitting infrastructure? The answer can be found in lock-in, demonstrating the intractability of coupled constraints. Technological innovations increased coal’s efficiency helping to increase its adoption in heating homes, powering trains and ships, and producing electricity in the 19th century. This made carbon-emitting infrastructure the centerpiece of the rapid growth of this time (Seto et al., 2016). Infrastructure systems were built around the new technology, and social systems began to emerge to regulate and capitalize on the energy source. As vested interests increased, stakeholders began lobbying to secure their investments, policymakers defend the technology to secure jobs for their constituents, and individuals are familiarized with coal-powered technologies and their conveniences (and, as mentioned above, people like routine). These rules and norms began to further embed coal as the primary choice of carbon, and then more

technological investments led to more policy and regulation. For instance, an energy charter treaty signed in 1991 (mostly involving European Union states) has provided the space for fossil fuel investors to sue governments transitioning to renewable resources (Kuppuswamy, 2022).

Once lock-in is recognized, the next step is to identify how to dismantle it to advance flexible, and more resilient, infrastructure. Occasionally, the reviewed lock-in articles asserted how to ‘unlock’ systems that have become entrenched, and the next section provides an initial overview of overarching strategies, followed by a synthesis of specific strategies within each domain.

3 UNLOCKING LOCK-IN

Several interrelated strategies have been proposed to ‘unlock’ locked in systems within technology, infrastructure, and carbon literature. Corvellec et al. (2013) concluded that “unlocking technology systems requires a combination of systematic efforts to promote alternatives, a critical mass or social and political recognition of a need for social action, and a focusing event that acts as a catalyst for concerns and initiatives.” The following subsections synthesize unlocking strategies from the emerging body of knowledge surrounding lock-in of technology, infrastructure, and carbon. This typology synthesis is coupled with application to critical infrastructure systems.

3.1 Economic Lock-in

Economic lock-in, a macroscale influence, is largely attributed to sunk costs (e.g., economies of scale) and loss aversion (Arthur, 1994; Foxon, 2002; Cantarelli et al., 2010; Hetemi et al., 2020). At its simplest, economic lock-in can be overcome when capital and operating costs of new technologies are lower than existing technologies (Seto et al., 2016). The most recommended strategy for breaking economic lock-in was for decision-makers to reevaluate appraisal methods (Wilson, 2013; Corvellec et al., 2013; Cairns, 2014; Seto et al., 2016). Appraisal methods could re-prioritize social and ecological capital alongside economic (Bordieu, 1987; Wilson, 2013; Corvellec et al., 2013), value conservation over efficiency (Seto et al., 2016), prioritize long-term objectives (Frantzekaki & Loorbach, 2010; Cecere et al., 2014); or recalculate the value of new investments and incremental adaptation versus long-lasting assets to consider cost tradeoffs of not transitioning or developing new cultural norms (Corvellec et al., 2013; Seto et al., 2016). For instance, it has been difficult to value the social and environmental co-benefits and impacts of nature-based solutions monetarily, making implementation difficult (van Oijstaeijen et al., 2020). There should also be a mindset shift within infrastructure organizations to accept that there may be a decrease in profit when switching technologies or maintaining a more diverse portfolio of technologies, i.e., economies of scope (Corvellec et al., 2013; Klitkou et al., 2013; Chester & Allenby, 2018) – niche markets can prove a useful tool to protect and fund research and development (Klitkou et al., 2015; Seto et al., 2016; Wesseling & van der Vooren, 2017). Other economic policies (e.g., purposefully creating stranded assets by encouraging a new technology, such as transitioning from nonrenewables to renewables) and incentives (e.g., encouraging alternative personal behavior and choices to influence the market, such as providing tax incentives

for electric vehicles) can help with cost allocation problems during technology transitions (Seto et al., 2016). Finally, it is important to acknowledge that economic lock-in can be perpetuated by the poverty trap, where marginalized communities do not have the monetary resources to abandon functioning infrastructure (Wilson, 2013). This provides an example where a cost allocation problem (or broadly, lock-in) becomes a moral dilemma.

3.2 Individual Lock-in

Individual lock-in influences at the microscale, where the action of a single decision-maker, or a small subset, can begin to perpetuate lock-in. As an infrastructure manager becomes more familiar with their role, learning effects can lead to a specialization, which is viewed positively in organizations due to an association with increased productivity (Klitkou et al., 2015). The infrastructure manager must balance exploitative and explorative design choices (Uhl-Bien & Arena, 2018). There is also the influence of informational increasing returns, collective action, and network externalities, where adopting the same technologies as collaborators can increase efficiency (Arthur, 1994; Foxon, 2002; Hetemi et al., 2020). This can be seen with automobile companies who are sharing electric vehicle charging infrastructure to encourage more adoption. Here, individual lock-in is interacting with institutional lock-in, as the institution influences the individual. The takeaway is to avoid becoming narrowly focused on a singular outcome due to biases early on in the decision-making process, and to revisit decision-making processes to ensure they are not reductionist (Cantarelli et al., 2010).

3.3 Institutional Lock-in

Institutional lock-in is distinctively intentional, where stakeholders are resolved to secure their own interests (Seto et al., 2016). This intentionality paired with the wide array of influenceable scales, ranging from organizational safety parameters to federal funding to global politics, provides the greatest opportunity to unlock infrastructure systems (Seto et al., 2016). Three dominant strategies emerge to address institutional lock-in: examining power, realigning missions, and implementing targeted policies. A focus on efficiency in institutions leads to coordination effects due to rules and norms, complementary effects based on existing relationships, institutional learning effects that lead to a status quo and repetitive decisions, and adaptive expectation effects which focus on one solution (Foxon, 2002; Cecere et al., 2014; Hetemi et al., 2020). These forces are difficult to disrupt because of the power asymmetries within institutions, where oftentimes only top-level management can realign long-term missions and objectives (Foxon, 2002; Cecere et al., 2014; Klitkou et al., 2015; Hetemi et al., 2020). Explicitly, top-mangement of infrastructure systems must place value in unlocking said systems in order to see change. By realigning an institution or organization in response to complexity, an institution would demonstrate increased plasticity and flexibility, which increases the likelihood of transitions without relying on shock events (Frantzeskaki & Loorbach, 2010; Seto et al., 2016). For example, institutions could also be more receptive to new views, which may inspire change in rules and norms (e.g., the adoption of industrial ecology in industrial systems) (Corvellec et al., 2013). Increasing collaboration capacity

is difficult as an introduction of more views also introduces more tension. However, leaders within infrastructure organizations may support practices such as information sharing and boundary-spanning by aligning organizational objectives, training employees and bringing them together, devoting time and resources to collaborative initiatives, and investing in adaptive and enabling leadership skills (Uhl-Bien & Arena, 2018).

With political willpower (another strong power influencing infrastructure systems at the macroscale), policies could be put in place that counteract lock-in within infrastructure systems. Basic research and development, niche market development, and financial incentives can create increasing returns for emergent technologies (Foxon, 2002; Klitkou et al., 2015; Seto et al., 2016; Wesseling & van der Vooren, 2017). By promoting diversity in technology and institutions, institutions can promote competition and reduce prices; further, they can guide transitions by placing regulations and taxes on entrenched technologies (Seto et al., 2016; Wesseling & van der Vooren, 2017). However, long-term objectives must be assessed when setting policies as intentional and incremental policy changes can just as easily unlock infrastructure as they can lock in infrastructure (Frantzeskaki & Loorbach, 2010; Seto et al., 2016). While transparency and adaptive capacity within politics would best serve lock-in management (Foxon, 2002), it is important to acknowledge growing polarization in politics (and beyond) suppresses these characteristics and maladapt toward cognitive inflexibility (Jung et al., 2019; Zmigrod et al., 2020).

3.4 Epistemic Lock-in

Infrastructure managers must be trained to engage with complex systems and environments; otherwise, their training will become increasingly inadequate (Allenby and Chester, 2018). Infrastructure managers must recognize the growing complexity of their systems and environments and reconfigure their processes to be better able to cope with surprise. At the university level, accreditation processes should be modernized to identify any areas of education that have become obsolete (e.g., competencies now feasibly completed by software or artificial intelligence) and update requirements to address novel competencies (e.g., cybersecurity) (Allenby & Chester, 2018). Further, the emphasis on efficiency must be balanced with instruction on adaptation and transformation to avoid perpetuating lock-in. This evaluation of education must be dynamic so that engineers continue to evolve at the same pace as the environment (Allenby & Chester, 2019). Epistemic lock-in is a macroscale influence. For example, most engineers, within the US, are trained to meet set quality standards (i.e., ABET accreditation); therefore, the accreditation develops relatively universal knowledge, assumptions, and biases in infrastructure managers. More generally, in combination with the institutional domain, these two domains are intertwined around knowledge systems – the practices and tools used within and across institutions (as well as individual training) to generate, validate, share, and utilize knowledge claims around the world (Miller & Muñoz-Erickson, 2018).

3.5 Technological Lock-In

Arguably, the other domains of lock-in lead to technological (or infrastructural) lock-in, where the interrelatedness and interdependence of infrastructure, combined with their long lifetimes, lead to entrenched technologies (Corvellec et al., 2013; Heres et al., 2015; Klitkou et al., 2015; Seto et al., 2016). Infrastructure systems persist as they reduce uncertainty, also known as adaptive expectations (e.g., an individual will buy a gas-powered car because they know for certain they will have access to a gas station, as compared to hydrogen-fueled vehicles) (Arthur, 1994; Foxon, 2002; Hetemi et al., 2020). Technology diversity (i.e., economies of scope) can help avoid this entrenchment through complementary coexistence (Foxon, 2002; van der Vleuten & Raven, 2006; Cecere et al., 2014; Seto et al., 2016). In regards to technological breakthroughs, there must be space for experimentation, innovation, and transformation within infrastructure design that emphasizes flexibility and adaptation at a systems level (Frantzeskaki & Loorbach, 2010). One opportunity is to utilize crises in existing technologies as an opportunity to adopt new technologies (Iwaniec et al., 2019, Cowan & Hulten, 1996). Still, infrastructure managers could also take advantage of the needs for maintenance, repair, and extension, creating opportunities for radical adaptation (Frantzeskaki & Loorbach, 2010; Corvellec et al., 2013). Another opportunity space is to create niche markets, which could provide a protective space for experimentation and innovation of new infrastructure (Cowan & Hulten, 1996; Cecere et al., 2014; Wesseling & Van der Vooren, 2017). This may also be referred to as ‘skunkworks’ (coined by Lockheed Martin), where a group is granted autonomy to explore new ideas (e.g., Bommer et al., 2002; Goldstein, 2008). A third opportunity can be found by identifying a change in consumer preferences and, in particular, utilizing early adopters (Cowan & Hulten, 1996; Cecere et al., 2014).

3.6 Social Lock-in

Social lock-in is driven by norms and expectations of infrastructure customers. Much of social interaction with infrastructural systems are based on routines and habits that reflect our collective expectations for services and norms related to appropriate use (Shove, 2003; Wilson, 2013; Corvellec et al., 2013). For instance, it is expected for infrastructure systems to provide 24/7 services which can lead to overdesigned systems (e.g., sizing a stormwater pipe much larger than usually necessary to account for a rare worst-case scenario). Infrastructure managers hold the majority of power over the design of infrastructure systems, but it is pertinent to understand how collective action may aid in unlocking systems. Wilson (2013) states that powerful leaders focused on a particular objective can spearhead a movement, and this directed attention can create the momentum needed for transformation. This involves empowering individuals (microscale) and the community (mesoseale), encouraging ownership of their knowledge and non-trivial participation in design decisions (Cairns, 2014; Seto et al., 2016). By building capacity within a community (e.g., bonding, bridging, and linking skills), infrastructure managers will be prepared (and better supported) to implement new solutions (Wilson, 2013; Corvellec et al., 2013; Cairns, 2014; Seto et al., 2016; McPhearson, Iwaniec, & Bai, 2016).

4 DISCUSSION

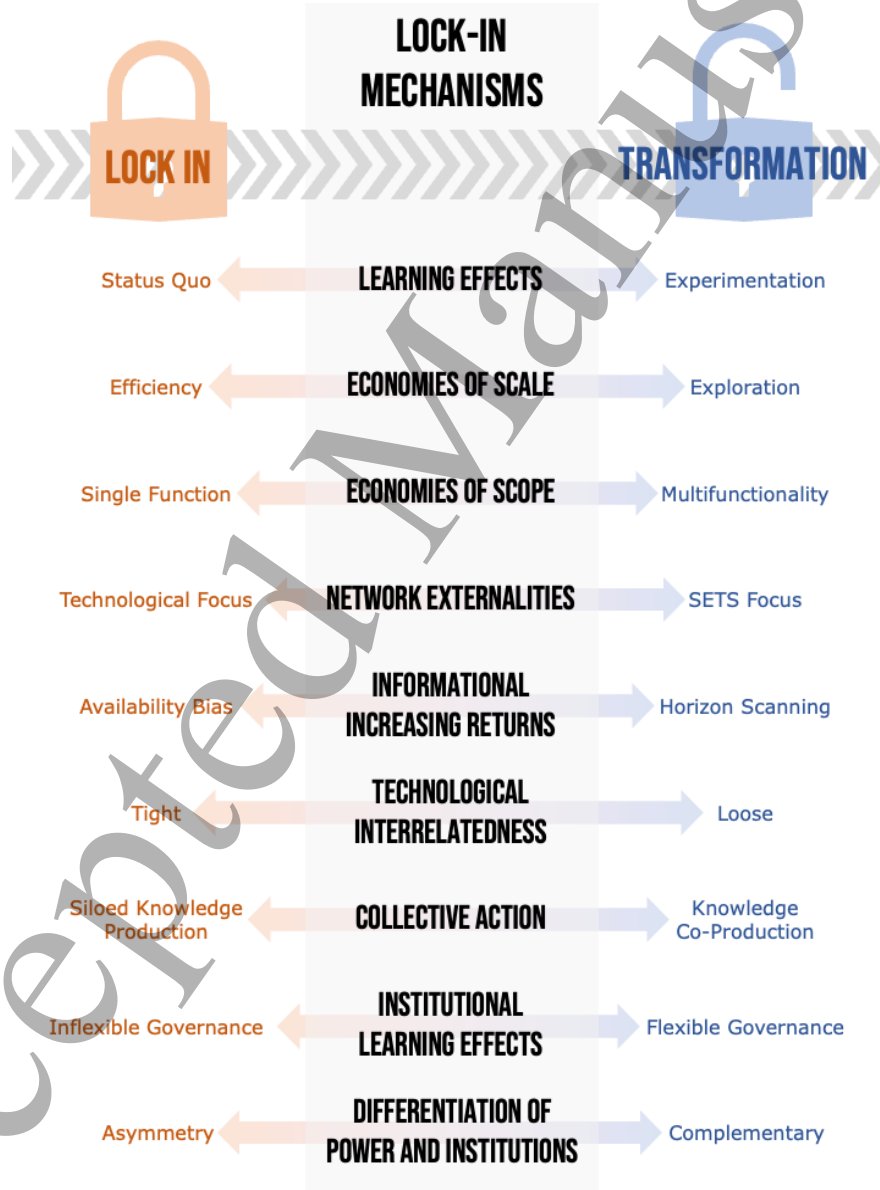
Infrastructure systems must be able to respond to increasingly complex and uncertain environments, and when infrastructure experiences lock-in, the system has limited capacity to expand its responses (Tainter, 1988). The capacity of infrastructure systems “to create the knowledge, processes, and technologies necessary to engage environment complexity” has been labeled *infrastructure autopoiesis*. Chester and Allenby (2022) state that to meaningfully engage with complex environments, an infrastructure system must have a variety of responses larger or greater than the variety created by the environment. Lock-in, therefore, can be viewed as a constraint upon the variety of responses that an infrastructure system is able to create; it is an agent against transformation. As a solution space becomes increasingly restrained by the domains of lock-in, the infrastructure system is increasingly prone to inadequacy or, at worst, failure. Therefore, the identification of lock-in influences is critical to avoid disruption due to complacency.

In parallel, as lock-in constrains infrastructure, the demands upon infrastructure perpetuate lock-in. Individuals, organizations, and institutions hold recognized value in infrastructure systems and the services they provide, which leads these actors to sustain the current, familiar structures (physical and governing) to maintain the value and the expected benefits (Tainter, 1988; Tainter and Taylor, 2014). This adherence to a familiar system or the status quo relates back to omission bias and procedural rationality discussed prior in Section 2. Furthermore, institutional solutions tend to accumulate rather than dissipate (Tainter, 1988), causing infrastructure systems to become stuck in a feedback loop while attempting to address growing complexity and continuing to deliver services. For example, the levees need to hold because the service of flood control needs to hold because there's a community abutting them, and because the community trusts the levees more development occurs (i.e., the levee effect). This feedback loop then leads to the accumulation of more institutional solutions, and built solutions such as a larger levee, so that the service delivery is maintained. Simply by ‘solving problems’ society becomes increasingly interconnected and complex (Edwards, 2002; Tainter and Taylor, 2014).

The complexity of infrastructure systems is leading to a normalization of failures (Perrow, 1984; Tainter, 1988; Kanoi et al., 2022). Infrastructure resilience, and specifically engineering resilience, is often defined by robustness and recovery rather than adaptation and transformation (Yodo & Wang, 2016; Helmrich et al., 2020), which may unintentionally perpetuate lock-in. If existing designs are experiencing increasing failures (e.g., climate change (Underwood et al., 2017; Bondank et al., 2018; Burillo et al., 2017)), it lends to question the aversion to experimentation and adaptation within infrastructure design. And if failure is already becoming normalized, it would be better to engage with failures from learning through experimentation and adaptation, than failures resulting from routine, engrained through lock-in. It is critical to understand the decision-making spaces in which infrastructure managers are operating. Experimentation and adaptation need to occur across social, ecological, and technological components of infrastructure

systems and engage with the six domains of lock-in. There are existing mechanisms of lock-in (as cataloged by Klitkou et al., 2015) that can be reframed to dismantle lock-in. These mechanisms have been introduced throughout the paper, but are listed explicitly in Figure 2, alongside dominant interpretations within locked in systems and potential reframings for transformation. A two-way arrow is used to connect the framings to emphasize that lock-in needs to be managed, not eradicated. This continuum of strategies represents broad systemic changes that can aid an institution toward being more agile and flexible to manage lock-in, but manage lock-in. The following text navigates these continuums.

Figure 2. Reframing Lock-in Mechanisms for Transformation



In order to create more resilient physical infrastructure, infrastructure institutions will need to re-evaluate their formal and informal governance structures for flexibility and examine *differentiation of power and institutions* and mitigate the power of vested interests (Wesseling & van der Vooren, 20117). This is not without obstacles as infrastructure managers are already inundated with information – information that is only multiplying in an increasingly connected world. *Collective action* through knowledge co-production within an organization, by creating interdisciplinary teams across siloed departments, and between organizations and stakeholders (e.g., frontline communities) can bring forward more diverse framings, ideas, and solutions from emerging information. Infrastructure systems must be willing to learn and be capable of learning at pace with the information they are receiving. *Learning effects*, including individual to *institutional* scales, have been interpreted as an opportunity to increase efficiency by reducing costly resources through the establishment of routines and standards, which can constrain the ability to learn (Klitkou et al., 2015).

By focusing on efficiency as an outcome of learning, infrastructure managers neglect resilience objectives (Markolf et al., 2022). *Economies of scale* (i.e., cost reductions from mass production), in particular, can reinforce efficiency and avoidance of exploration for alternative solutions. *Economies of scope* lead to cost reductions from diversification; diversification in infrastructure systems can occur via modular and decentralized structures, e.g., variety in technologies throughout the physical network or diversity in decision-making power within an institution (Gilrein et al., 2019; Helmrich et al., 2021). Experimentation offers another opportunity for learning that can promote resilience. For instance, rather than optimizing for one objective, infrastructure systems could become multifunctional, where the system provides more than one service by satisficing amongst multiple objectives and assessing *network externalities* across social, ecological, and technological systems (SETS) components. An example is available in safe-to-fail infrastructure, a consequence-based management strategy that prioritizes risks to minimize harm by accounting for expected failure in the design phase and educates infrastructure managers to monitor for unexpected failures as well as manage the consequences across SETS components (Park et al., 2013; Kim et al., 2019; Yu et al., 2020, Kim et al., 2022).

By engaging with variety, infrastructure systems could move toward loose-fit design, avoiding restrictive *technological interrelatedness*, where existing technologies prevent the incorporation of new technologies. Loose-fit design encourages flexibility and responsiveness through increased autonomy (physical and institutional), where the system can co-evolve with the environment (Foxon, 2011; Chester & Allenby, 2022). Finally, it is important to recognize *informational increasing returns* where growing momentum of emerging strategies will lead to more adoption. Infrastructure managers should confront assumptions and biases to avoid instances of availability bias (i.e., disproportionately relying upon available information). A way to counteract this is to conduct horizon scanning, a practice of identifying new, emergent opportunities toward promoting increasing adaptive capacity to respond to complexity within a system.

5 CONCLUSION

As the environment becomes increasingly complex, and thereby unpredictable, it is necessary to adapt and transform infrastructure systems. Due to lock-in, a sub-optimal system may appear to be rational over time; however, the crisis occurs when the system is unable to evolve fast enough to meet emergent internal and/or external challenges, which will happen more frequently in the Anthropocene. While ignoring lock-in may be a moral dilemma now, it may become a question of ethics as communities recognize their infrastructure is becoming increasingly unreliable. If systems are already failing due to the inability to keep pace with changing conditions, infrastructure managers should maximize learning from these events through experimentation, adaptation, and transformation. The omission bias must be directly confronted. Infrastructure managers must make a decision between a locked in, faltering but familiar system or a changing, responsive but novel system, where both are, inevitably, accepting higher levels of risk than typically accustomed. One example of risk allocation arises when substituting new technology in place of historically reliable technology. Cost and benefit distributions change – seldomly accruing to the same interest groups or institutions – meaning that the logistics of lock-in management are inherently difficult. Furthermore, managing transitions in infrastructure systems must also include careful attention to how social life – that has co-evolved with these systems – will have to change as well. By identifying domains of lock-in, recognizing the opportunities and challenges they present, and assessing potential strategies to unlock infrastructure systems as needed, managers can critically reflect and create roadmaps toward more resilient futures or, in other words, manage short-term disturbances while maintaining a long-term perspective toward system transformation (Corvellec et al., 2013; Chester & Allenby, 2018; Gilrein et al., 2019).

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7 DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study.

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