Concepts and Practices for Transforming Infrastructure from Rigid to Adaptable

by

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ABSTRACT

Infrastructure are increasingly being recognized as too rigid to quickly adapt to a changing climate and a non-stationary future. This rigidness poses risks to and impacts on infrastructure service delivery and public welfare. Adaptivity in infrastructure is critical for managing uncertainties to continue providing services, yet little is known about how infrastructure can be made more agile and flexible towards improved adaptive capacity. A literature review identified approximately fifty examples of novel infrastructure and technologies which support adaptivity through one or more of ten theoretical competencies of adaptive infrastructure. From these examples emerged several infrastructure forms and possible strategies for adaptivity, including smart technologies, combined centralized/decentralized organizational structures, and renewable electricity generation. With institutional and cultural support, such novel structures and systems have the potential to transform infrastructure provision and management.

DEDICATION

To Dr. A. Brew, who was and still is always there for me, and is always excited to see me when I come home.

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Introduction

Today's infrastructure face the concurrent challenges of increasing uncertainty in the demands and conditions in which they are expected to perform, and their rigidity. It is becoming apparent that the Earth is entering a period of non-stationarity (Adger, 2005; Milly et al., 2008; O'Brien & Leichenko, 2000). Furthermore, as technology develops more rapidly (e.g. Smart Cities and coupled information and communication infrastructure; Grinin & Grinin, 2016; Perez, 2009) the complexity of the technological world and the built environment surpasses the ability of society and governing institutions to fully grasp, let alone respond to the challenges it presents (Arbesman, 2016; Marchant, Allenby, & Herkert, 2011). With infrastructure often serving as the front line for impacts from increasing non-stationarity (system properties fluctuate within an ever-changing envelope of variability; see Lins, 2012; Milly et al., 2008) and complexity, in the context of climate stressors and hazards, the need to build adaptive capacity for infrastructure systems becomes imperative.

Current infrastructure systems are founded on assumptions of stationarity in that they are rooted in risk-based analysis along with fail-safe (designed with the assumption of infallibility) approaches that drive toward more rigorous and permanent infrastructure, and thus lack the capacity to readily change in response to new or unexpected conditions (Ahern, 2011; Kim et al., 2017). Such approaches result in infrastructure that operate consistently within a limited set of predictable occurrences, but are inherently brittle to unpredictable, unexpected, and unprecedented (i.e. surprise) events. Further, infrastructure cannot be easily updated (without significant expense) in response to such situations, and prior decisions continue to restrict current and future alternatives (here referred to as path dependency and lock-in (Corvellec, Campos, & Zapata, 2013)). Thus, with a systematic under-appreciation for less likely conditions or the potential for unknown dynamics, infrastructure are built in rigid fashion. Taking into account the dynamic between a future of non-stationarity and the built-in rigidity of infrastructure, legacy systems often have insufficient capacity to adapt to changing Earth systems.

In light of these challenges, previous research has aimed at unearthing the attributes and structures of adaptive physical and institutional systems (Ahern, 2011; Bernardes & Hanna, 2009; de Neufville & Scholtes, 2011; Duncan, 1995; Kincaid, 2000; Sherehiy, Karwowski, & Layer, 2007; Yusuf, Sarhadi, & Gunasekaran, 1999). Chester and Allenby (2018) honed in on such works to conceptualize adaptive infrastructure as consisting of both agility and flexibility, respectively, the ability to maintain function in both physical structure and institutional rules despite a non-stationary future, and the ability to respond to changes in demand beyond regular or incremental changes. To describe design and management principles associated with agile and flexible systems, they introduced a set of ten competencies (Table 1). These competencies were collected from successful implementations of agility and flexibility in other industries, and were positioned by Chester and Allenby (2018) to support infrastructure and infrastructure managers to adapt and plan amidst perpetual changes in climate, technology, and socio-ecological conditions. Yet, little is known about how these competencies might be operationalized in infrastructure.

Table 1: Characteristics of adaptive infrastructure in contrast to current planning and design practices (Chester & Allenby, 2018).

Competency	Current	Adaptive
Perception & Responsiveness	Prioritizes perpetuation of existing designs	Roadmapping
Perception, Responsiveness, & Technical Structure	Obdurate Design	Design for obsolescence
Technical Structure	Hardware focused	Software focused
Technical & Institutional Structures	Risk based	Resilience based
Technical Structure	Incompatibility	Compatibility
Technical Structure	Disconnected	Connectivity
Technical Structure	Non-modular design	Modularity
Institutional Structure	Mechanistic	Organic
Institutional Structure	Culture of Status Quo	Culture of Change
Perception & Responsiveness	Discipline-focused Education	Trans-disciplinary Education

This paper builds on the concept of adaptive infrastructure by grounding the concept with practical observations curated from a literature review of infrastructure that embody at least one of the ten competencies, followed by a discussion of what these findings mean for infrastructure, how the results support or expand concepts of adaptive capacity, and opportunities and limitations in future infrastructure systems. The goal of this work is to systematically profile case study examples of infrastructure that exhibit successful implementations of adaptivity, as well as identify the current state, emerging trends, and gaps towards successful implementation. A focus on in-practice and operational examples of agility and flexibility in infrastructure offers a glimpse into the characteristics of novel infrastructure toward illuminating potential strengths, difficulties, and degrees of practical feasibility with respect to the implementation and management of infrastructure with agile and flexible qualities. Such insights can inform researchers, planners, and engineers towards building adaptive capacity in infrastructure. Lastly, this work aids in setting targets for further research on adaptive infrastructure.

Approach

Infrastructure were framed as composed of physical and institutional components, with a focus on electrical power, water, and transportation (roadway) systems. Chester and Allenby's (2018) ten characteristics (Table 1) were then used to develop a literature review of implementations of and planned projects around adaptive infrastructure. The methodology used keywords in web searches of scholarly and open sources to identify articles, case studies, and products related to infrastructure (see Table 2 for a curated list of keywords).

Table 2: Examples of keywords used for identifying infrastructure case studies.

- Modular
- Multi-objective
- Flexible Transport Systems
- Multifunctional
- Adaptive
- Functional Diversity
- Smart
- Demand-oriented Infrastructure Service Delivery
- Operational Flexibility
- Adaptive Capacity
- Responsive
- Dynamic
- Regenerative Design
- Process-Oriented
- Resilient

For example, Searns (1995) describes the "multi-objective" and "connectivity" attributes of greenways in terms of adaptive urban landscapes. Often, the word "flexibility" itself is used in terms of infrastructure goals or properties (e.g. "operational flexibility", as in Ulbig & Andersson, 2015). Thus, as the adaptive characteristics themselves serve intuitively as initial keywords, synonyms were then derived as search results to find exemplary cases. Keywords were applied across all infrastructure types and subtypes (where, e.g., wastewater is a subtype of water infrastructure) to ensure equal focus on each. Case studies in each infrastructure were reviewed across the applicable competencies to both provide a profile of adaptability in that infrastructure system, but also to show a broader range of competencies that are significant to that infrastructure. This additionally showed the variety of infrastructure across which a competency might be relevant.

Initial criteria for interpreting cases were based on how well they exemplified the competencies in respect to the definitions outlined in Chester and Allenby (2018). The process of trying to parse distinctions between the original context these definitions were drawn from and the context of infrastructure called for refined and clarified definitions toward this application (updated definitions are shown in Table 3). Changes were generally minor, such as generalizing a definition from a specific domain to be more broadly applicable across many infrastructure domains, or to extend to physical and/or institutional attributes. For instance, the word “component” was updated to “components or capacity” in respect to the initially adopted definition of modularity by Duncan (1995) in Chester and Allenby (2018). In other occasions, the definition was refined for further specificity or clarity, such as “continuous and/or reflexive” added as a prefix to “experimentation” for culture of change (Sherehiy et al., 2007).

Table 3: Competencies of agile and flexible infrastructure.

Competency	*Definition*
Modularity	The ability to readily add, remove, or modify individual technical or institutional components without significantly disrupting or affecting other components and in turn, the overall system.
Connectivity	The degree to which infrastructure components can readily interact with other components within the system and with the components of other systems.
Compatibility	The ability to integrate into a common or shared network of rules, material, energy, and information flows.
Hardware-to-Software/ -Services	Substitution of services or information-based mechanisms in place of physical components and mechanical processes.
Culture of Change	Management, design, and planning practices that embrace continuous and reflexive experimentation, innovative strategies, and "learning by doing".
Planned Obsolescence	Planning practices based on the view that conditions may change, and an awareness of potentially creating path dependencies that may complicate future adaptivity in light of potential changes regarding functions, demands, and Earth systems.
Roadmapping	Managing short-term demands and urgencies along with an intentional long-term perspective toward developing structures that cope with rapid evolution of systems and deep uncertainty.
Organic Structure & Management	An organizational structure characterized by a more decentralized decision-making authority, fluid division of labor, and transparent communication practices.
Risk-to-Resilience	Awareness of non-stationarity in Earth Systems and a focus on building adaptive capacity, anticipation, experimentation, and learning, in lieu of a probabilistic and deterministic risk-based approach.
Transdisciplinary Education	Fostering education that acknowledges the diversity of actors, institutions, and ways of knowing involved in the design and management of infrastructure as a complex system.

At times, the revised definitions by themselves were insufficient to make a clear determination of whether a case displayed a specific competency. Additionally, because many examples are still in a concept stage, pilot program, or in general nascent, detailed assessments that describe how well a system has shown to be able to adapt are not well established. Such cases were then further interpreted more holistically to determine if they appeared to contribute more greatly to increasing adaptive capacity in respect to legacy infrastructure.

Ultimately, data included academic literature, reports, news articles, web articles, and company or organizational websites. Most cases that resulted are from the United States, which is most likely a function of the search engines used, location-based results, and English keywords. Three main infrastructure categories, water, electrical power, and transportation (roadways), formed the focus of the infrastructure data. Once compiled, cases were catalogued, reviewed, and interpreted to draw insights into the overall content that emerged. See agileflexible.resilientinfrastructure.org for a database with short descriptions along with tags for respective competencies, infrastructure domains, applicability to physical or institutional properties, and pertinence to climate change adaptation.

Synthesis of Findings

Water

Managing fluctuations in potable water quality and quantity. Potable water infrastructure, from sourcing to treatment and distribution, are designed for high reliability under a range of conditions anticipated from historical observations. Yet, these systems are vulnerable to events outside the bounds of historical variability. Climate change, increasing demand, and long-term overuse of aquifers threaten the quality and availability of water, which are issues that cannot be easily managed by existing water supply and treatment systems (Delpla, Jung, Baures, Clement, & Thomas, 2009; Vörösmarty, Green, Salisbury, & Lammers, 2000; Whitehead, Wilby, Battarbee, Kernan, & Wade, 2009). Agile water treatment in the future will likely need to treat a wider range of water qualities in the face of these threats. Resilience-based treatment that mitigates water quality and quantity challenges, rather than risk-based treatment design which handles uncertainty through oversizing and strengthening approaches, offers benefits under non-stationary conditions. Further, distribution pipe systems cannot be easily upgraded to meet changing population needs, and water main breaks disrupt service and cause damages to roadways. Modular water treatment offers the option to operate on a decentralized basis while minimizing inflexible distribution infrastructure.

Modular water treatment systems can add flexibility by reducing or eliminating the need for distribution. Modular water treatment could be combined with, for example, rainwater collection or wastewater reuse to supply potable water needs for residences or commercial buildings. In contrast, existing water distribution systems need extensive upgrades and upsizing to serve increasing populations. Ceramic hollow-fiber membrane filters, for example, are modular and can be operated at a variety of scales, ranging from individual drinking water needs, as in the LifeStraw technology, to a 38-million-liter-per-day water treatment plant in Parker, Colorado (Ing, 2005; Lifestraw, 2018; Parker Water & Sanitation District, 2018).

Decentralized potable water systems are common in recent literature (for example, Domènech, 2011; Peter-Varbanets, Zurbrügg, Swartz, & Pronk, 2009) and Lee, Sarp, Jeon, and Kim (2015) described how connectivity to ICT can enhance decentralized water networks. Notably, the research uncovered case studies mostly in water treatment and sourcing, with none in water distribution. Decentralized systems rely on agile water treatment and remove the need for water distribution systems. This could imply that elements of decentralized, networked water infrastructure, particularly the reliance on modular components and the absence of rigid distribution systems (supporting planned obsolescence), support adaptability. However, it is unclear whether fully decentralized water systems are the most adaptable based on these findings, and in any case existing centralized systems may not be able to transition to decentralized structures (not to mention efficiency, reliability, and equity challenges such structures bring). Zodrow et al. (2017) suggest semi-centralized or combined centralized and decentralized systems. Also, existing centralized water distribution systems are important for providing water to extinguish fires, and research is needed on how systems that incorporate decentralized elements can provide this critical service.

The risk-to-resilience competency appears in water treatment through the capacity to manage changes in water quality and quantity, allowing treatment plants to treat various water qualities from different sources or even switch sources if necessary. Existing water treatment and distribution systems are designed for a known range of quantities and contaminants, often from a consistent water source, causing problems if the source runs dry or is contaminated. For example, powdered activated carbon can provide this treatment flexibility through its ability to treat a wide variety of contaminants at once, and to be used only when needed in the treatment process (Mailler et al., 2014; Margot et al., 2013; Najm, Snoeyink, Lykins Jr., & Adams, 1991). The City of Los Angeles used the risk-to-resilience competency in water sourcing by creating a plan for collecting and storing stormwater to provide potable water, using green infrastructure and other strategies (Chau, 2009; Villaraigosa, 2008). The plan aims to reduce the city's dependency on nonlocal water resources, improve reliability of the water system, reduce demand for irrigation and stress on groundwater resources, and generally mitigate climate change stressors in the water supply system. Finally, wastewater recycled for potable use can be more resilient to climate stressors than surface or groundwater sources as wastewater quantities closely follow water use quantities (Levine & Asano, 2004).

Adaptive wastewater reuse. Agile and flexible wastewater infrastructure can simultaneously manage issues of sustainability, buffer impacts from flow non-stationarity, and obviate pipe network inflexibility. Much like potable water systems, wastewater treatment currently lacks agility to stressors such as demand or quality changes (e.g. from increased water conservation measures (DeZellar & Maier, 1980) or infiltration and inflow into pipe networks (National Small Flows Clearinghouse, 1999)). Collection networks have little ability to rapidly respond to population changes, and failures have drastic environmental and human health consequences while being difficult and costly to repair (Matthews, 2016; Tjandraatmadja, Burn, McLaughlin, & Biswas, 2005). Moreover, climate change and population growth have brought attention to how wastewater reuse may be required in future water systems to mitigate water demand stress (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007; Asano & Levine, 1996; W. Lee et al., 2016; Levine & Asano, 2004; Verstraete & Vlaeminck, 2011).

Agile wastewater treatment technologies differ from conventional (and rigid) technologies in that they exhibit resilience over risk-based designs often by having the capacity to handle variability in inflow rate, quality, and contaminants. Flexible and agile wastewater treatment plants have the ability to treat a wide range of types and concentrations of contaminants and to be scaled up (or down) as demands change. Two examples of treatment systems that can operate under a wide inflow water quality range are powdered activated carbon and continuously-backwashing sand filters. For example, powdered activated carbon can be stored and used for treating a wide variety of contaminants (such as petrochemicals and organic compounds) if the need arises (Meidl, 1997). Continuously-backwashing sand filters provide better, more efficient contaminant removal over a wider range of contaminants when compared to conventional media filters (England, Darby, & Tchobanoglous, 1994). Additionally, ceramic hollow-fiber membranes and continuously-backwashing sand filters are modular and thus can be operated in series to provide higher-quality effluent, or in parallel to increase treatment capacity (Peter-Varbanets et al., 2009; Turlington, de Neufville, & Garcia, 2017). Constructed wetland wastewater treatment systems are highly flexible in terms of treating varying wastewater quantity and quality, particularly for removal of nitrogen and trace contaminants, though they can be difficult to scale up if land space is restricted (Vymazal, 2010). Using resilient, flexible wastewater technologies recognizes non-stationarity in future influent water qualities and quantities and, to an extent, they can adequately treat such variations.

As in potable water infrastructure, adaptive wastewater infrastructure tend to be more associated with decentralized treatment than centralized (e.g. Libralato, Ghirardini, & Avezzù, 2012; Opher & Friedler, 2016; Righi, Oliviero, Pedrini, Buscaroli, & Della Casa, 2013; Tchobanoglous, 2002; Tjandraatmadja et al., 2005; Zodrow et al., 2017). No examples emerged for collection network hardware. Decentralized wastewater treatment and reuse can be considered an example of the hardware-to-services competency by reducing or removing the need for collection networks (Asano et al., 2007), and support planned obsolescence by being easy to replace and upgrade to better reflect demand or external conditions. Wastewater reuse is especially conducive to decentralization (Asano et al., 2007). Water can be recovered for groundwater recharge or landscape irrigation among many other uses (Asano & Levine, 1996; Meneses, Pasqualino, & Castells, 2010), without using extensive collection infrastructure, if the systems are decentralized. One innovative system, the Solar Optics-based Active Panel, recovers water, nutrients, and energy by using nanoparticles and sunlight to disinfect greywater, which is recirculated throughout a building to recover thermal energy, then reused for nonpotable applications (W. Lee et al., 2016). Again, though it appears that decentralized wastewater treatment and reuse systems hold many agile and flexible competencies, it is unclear what configuration of centralized and decentralized system aspects is most adaptable.

Resilient stormwater and flood control services. Resilient stormwater infrastructure practices recognize that current risk-based stormwater and flooding management practices often exacerbate flooding issues in the long term (Di Baldassarre et al., 2013; Di Baldassarre, Castellarin, & Brath, 2009). Existing systems are designed for a specific storm intensity (e.g. a 100-year storm), but this design process means they may fail catastrophically in larger storms. In contrast, the Room for the River program in the Netherlands mitigates flood impacts not through pipes or levees, but by allowing the river to flood and retreating urban areas from the expanded flood zones (Rijke et al., 2014). This safe-to-fail system better manages unanticipated flood events by acknowledging flood conditions outside the typical return period.

Green infrastructure can offer risk-to-resilience through a variety of climate adaptation functions (European Commission, 2012; Gill, Handley, Ennos, & Pauleit, 2007). In particular, it slows runoff and does not fail catastrophically like levees or dams. For example, the Indian Bend Wash in Scottsdale, Arizona provides public park space, active transport infrastructure, and enhanced ecosystem services in its safe-to-fail drainage structure rather than a large, single function concrete drainage way (Collins et al., 2011; Kim et al., 2017). Permeable pavement systems address the generation of runoff, thus using a hardware-to-services competency in replacing some stormwater pipe networks or storage with the service of infiltration (Eckart, Sieker, Vairavamoorthy, & Alsharif, 2012; Scholz & Grabowiecki, 2007; Winston, Dorsey, Smolek, & Hunt, 2018). Such systems are modular through the ability to add capacity where needed even on rooftops. However, it should be noted that green infrastructure are not in and of themselves agile or flexible technologies. Only certain examples have agile or flexible competencies; i.e., simply planting trees in a city does not necessarily constitute adaptive stormwater management.

Stormwater information technology. Traditional stormwater management systems are beginning to integrate ICT infrastructure, utilizing the hardware-to-software and connectivity competencies (see Feigenoff, 2017; D. Hill et al., 2014; Kerkez et al., 2016; Opti, 2018). One unconventional example is mobile applications to crowdsource flooding information. App users both generate and use data on the location and intensity of a flood, allowing people to avoid dangerous areas and infrastructure managers to find where repairs may be most needed (G. Hill, 2017; Pratt, 2016). Another example is equipping stormwater management systems with sensors and controllers so that discharge rates can be adjusted based on current storage and weather forecasts (Kerkez et al., 2016). By using such information-based mechanisms, infrastructure managers can more safely and efficiently redirect traffic, plan repairs, and direct emergency responders.

For a conceptual layout of how these agile and flexible water infrastructure components may look in an integrated system, see Figure 1.

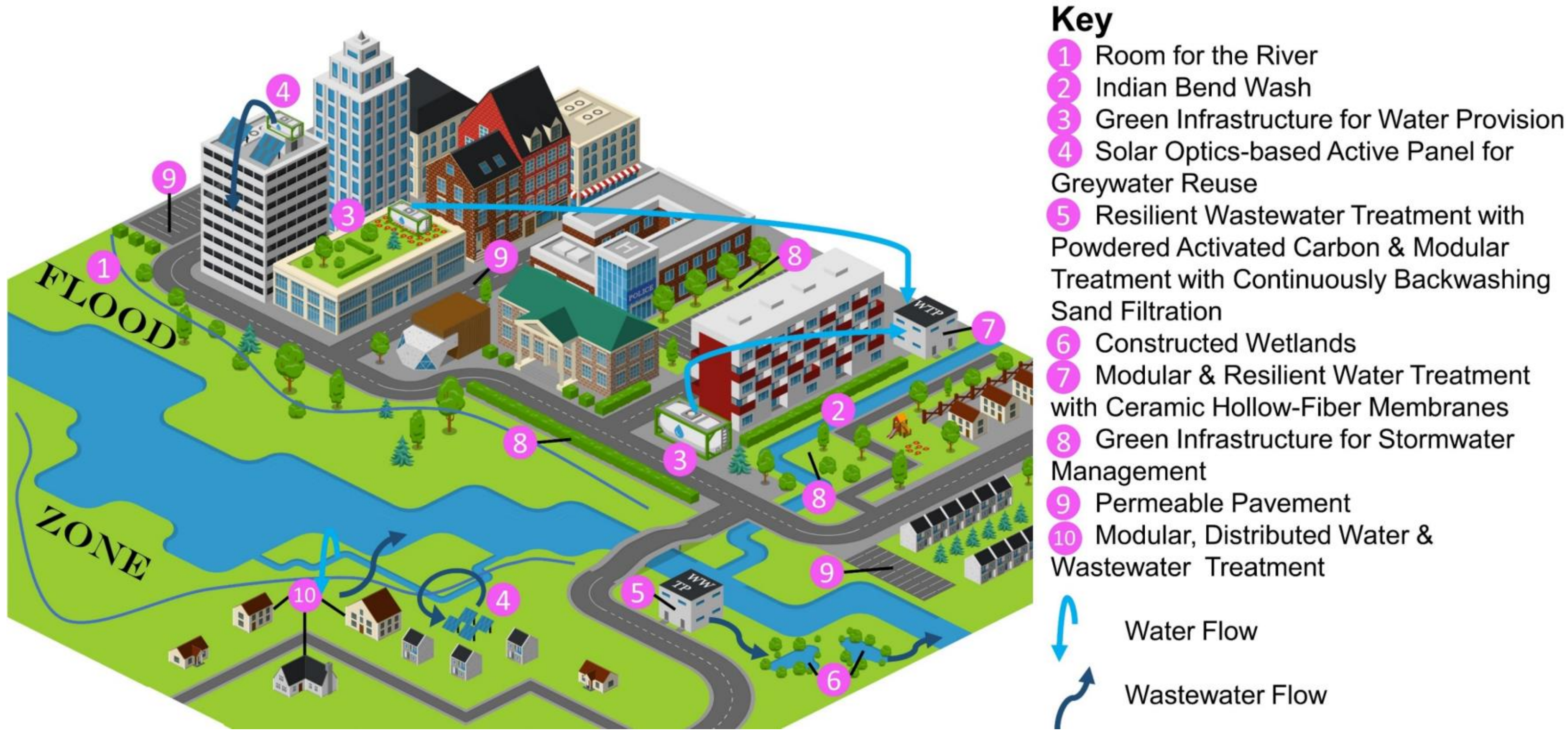

Figure 1: Future water system including both centralized and decentralized components, resilient treatment processes, and sustainable water reuse.

Electrical Power

Adaptive electrical power systems reflect recent trends such as sustainability, decentralization, and smart technologies. New electrical power generation capacity in the United States tends to be renewable rather than non-renewable, a trend that is expected to continue in coming decades (USEIA, 2017, 2018). At the same time, the popularity of decentralized electricity technologies such as microgrids, home batteries, and virtual power plants is growing. Many of these technologies utilize renewable electricity generation technologies, and allow generation to be more interspersed with distribution. Given this increasing integration of electricity generation and distribution, the three major components of electrical power infrastructure (generation, transmission, and distribution) were considered in tandem.

Renewable energy systems such as microgrids offer energy system flexibility through modularity, connectivity, and compatibility. Existing centralized electricity generation relies on transmission lines (that result in losses) and extensive fuel supply chains, both of which may be threatened by non-stationarity in climate, global fuel supply, international politics, regulations, and cost (Bouffard & Kirschen, 2008). In contrast, microgrids are small, interconnected electricity generation and distribution systems, utilizing the competency of modularity and connectivity to allow the creation of a scalable, networked electrical grid. Distributed generation and microgrids are also compatible with larger electrical grids (Kaundinya, Balachandra, & Ravindranath, 2009), and can utilize connectivity to coordinate the balance between demand, storage, and supply. Shipping container solar microgrid systems have recently been used in hurricane disaster relief efforts in Puerto Rico (Janko, Atkinson, & Johnson, 2016). Such systems are easily transported and can include batteries for improved reliability (Martin, 2017).

Resilience in the electricity sector creates adaptive capacity by mitigating uncertainties between demand and supply to prevent service loss. Current electrical systems operate with electricity generation attempting to coordinate with demand, both of which are increasingly unpredictable on scales from daily to decadal under stressors such as climate change (Mideksa & Kallbekken, 2010; van Vliet et al., 2012). Virtual power plants are a novel electricity distribution model that creates small groups of electricity customers under one pricing or demand response program, based on use characteristics and location (Zurborg, 2010). With virtual power plants, utilities can more accurately forecast available resources and demand conditions and redistribute electricity to respond to changes (Peik-Herfeh, Seifi, & Sheikh-El-Eslami, 2013). This functionality is enabled by software and ICT to coordinate rapid responses, representing the connectivity and hardware-to-software competencies (Andersen, Poulsen, Decker, Traeholt, & Østergaard, 2008).

The risk-to-resilience competency also manages uncertainties in electricity supply and demand by mitigating changes in each, which existing systems are not well equipped to manage. Electricity storage technologies support this competency by creating a buffer between generation and demand, much like tanks in potable water systems (Symons, 2001). For example, the Tesla battery bank in Australia was able to mitigate a service outage by responding in microseconds to a disruption in generation (Fung, 2017). Another electricity storage system proposed is inherent in Vehicle-to-Grid (V2G) technology (Fang, Misra, Xue, & Yang, 2012; Lund, Lindgren, Mikkola, & Salpakari, 2015). V2G utilizes modularity, connectivity, and compatibility to integrate with the grid and operate flexibly anywhere vehicles might be located. Batteries are critical components of microgrids (Lidula & Rajapakse, 2011).

Modular electricity generation allows electrical grids to more easily restructure capacity following changes in demand. Renewable energy technologies (especially solar panels) support this functionality, and tend to be more locally available than fossil fuels and less interdependent with fuel production and transport. By comparison, centralized electricity generation and transmission can take years or decades to develop, particularly in the case of nuclear power plants (Kaplan, 2008). Several sources suggest multi-scale electricity generation including both centralized and decentralized systems as most adaptive (e.g. Bouffard & Kirschen, 2008; Kaundinya et al., 2009). Distributed generation using fossil fuels may not be cost effective or adaptive, especially considering local air quality impacts and the interdependencies with fuel supply infrastructure (Gullì, 2006). In general, there did not appear to be any examples of adaptive non-renewable electricity generation for these reasons. Thus, it appears that modular, renewable energy will play a key role in improving the adaptive capacity of electric power generation moving forward.

Novel electricity system technologies often share the competencies of connectivity and compatibility in tandem. Battery technologies in large units or decentralized in V2G technology are compatible with electricity from all sources and help make these sources compatible with the rest of the grid (Fang et al., 2012; Fung, 2017); they also integrate well with ICT. Virtual power plants encourage connection between grids and communication between different generation and demand areas, and are compatible with existing electrical grids (Andersen et al., 2008; Zurborg, 2010). Microgrids can enhance existing systems by providing a renewable, independent energy source (Janko et al., 2016; Martin, 2017). Connectivity and compatibility in electrical systems may appear together in agile and flexible electricity systems to allow integration within shared energy and information systems (both of which are electronic), and bridge between electricity generation and demand.

In the future, the electrical grid is expected to increasingly utilize decentralized generation technologies (Fang et al., 2012), whether in addition to existing centralized infrastructure or by fully replacing centralized components. This represents the hardware-to-services competency for transmission systems, through the ability to replace transmission lines with electricity service that can be made available where needed. Several sources noted the lack of research relevant to adaptive transmission infrastructure as compared to generation and distribution (Li et al., 2010), particularly in the smart sector (Jiang et al., 2009). However, the embedding of ICT and smart systems is a commonly discussed pathway to agility in electricity transmission systems, and another example of the hardware-to-software competency (e.g. Bose, 2010; Jiang et al., 2009; Li et al., 2010).

For a conceptual layout of an agile and flexible electrical power system, see Figure 2.

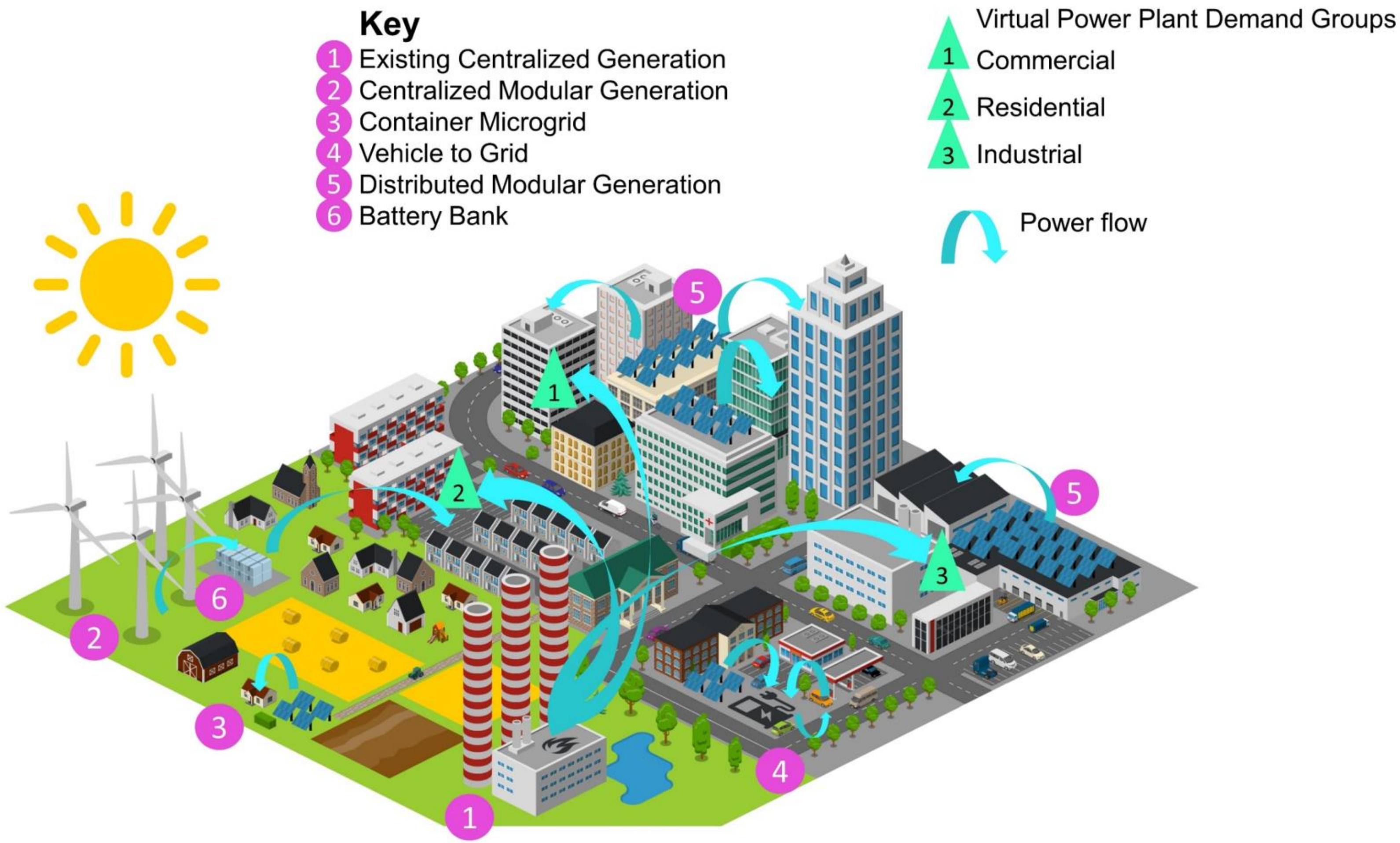

Figure 4: Future electrical power system including storage, centralized and distributed generation, and smart, dynamic control networks.

Transportation

Adaptive roadway services. Smart technologies enable roadways to add adaptive capacity through the hardware-to-software competency (note that smart and 'hardware-to-software' overlap but are not synonymous). Smart traffic signals and smart street lighting systems incorporate sensors coupled with control and response abilities allow roadways to adjust to needs. Generally, traffic signals are pre-set to expected conditions or utilize vehicle sensors. Smart traffic signal camera sensors are more adaptive by responding to accommodate intersection travelers outside the conventional design range, which supports the risk-to-resilience competency (Goodall, Smith, & Park, 2013; VisionSystems Design, 2008). Next, smart street lighting networks use sensors to determine where street lighting is or is not needed based on locations of vehicles or pedestrians to improve energy efficiency (Escolar, Carretero, Marinescu, & Chessa, 2014). Street lights are a promising avenue for adding sensors, as they are ubiquitous and already connected to electrical infrastructure. Some sensors can promote public safety by sensing noise disturbances (for example, using machine-learning algorithms to identify gunshots) and directing safety officials to respond (Kwang, 2018; Scott, 2016; Shotspotter, 2018). Mobile applications can allow drivers to adapt their driving and parking plans depending on traffic and parking space availability (Streetline, 2018). The city of Syracuse, New York uses sensors on their pothole-filling trucks (DuraPatchers) that automatically record when and where a pothole has been filled, and automatically upload the information to an online database (City of Syracuse, 2018). Using these data, infrastructure managers can visualize where roadways are deteriorating most and direct their attention to the areas that need rehabilitation. In general, smart technologies for roadways allow communication between roadway networks and across other networks (such as other transport modes or emergency services), collect data, and provide more accurate controls for roadway operations using the connectivity competency.

Both the hardware-to-software and hardware-to-services competencies are exemplified by telework, i.e., working over a virtual communications network rather than commuting. The option to work remotely allows users to choose to telecommute, which over the long term can reduce roadway capacity needs (Ferguson, 1990; Winters, 2000). The Blue Line Televillage pilot project in Compton, California expanded on the telework concept to provide a telework center, which functions as a virtual village center by providing virtual services such as classes, spaces for telework, videoconferencing, and banking (Siembab, 1996). The pilot project shifted travel away from cars towards public transit and walking, increased ICT network access with benefits to local small businesses, and promoted greater community and public involvement (see also Ledgerwood & Broadhurst, 1999). Feitelson and Salomon (2000) found telecommunications to be the most flexible compared to air, rail, and highway transportation, largely because of the much smaller need for rights-of-way and less central control in telecommunications networks. However, telework systems need broader institutional and cultural support before they make significant dents in the current transportation system.

Automobiles of tomorrow. Similar to right-of-way infrastructure, smart technologies and hardware-to-software hold many potential transformations for vehicles through improving efficiency, access options, and safety. Connected vehicle technology can enable the rapid communication of information about roadway conditions to travelers and managers (ITS, 2015; Lu, Cheng, Zhang, Shen, & Mark, 2014). The two-way connection between travelers and infrastructure allows immediate response to traffic and roadway conditions, and allows infrastructure managers to redirect traffic smoothly and safely. Connected vehicle technology could coordinate within and between vehicles and users to rapidly adapt to changing situations, potentially to the scale of handling an evacuation event, representing the risk-to-resilience competency.

Smart public transit systems incorporate ICT infrastructure in public transit structures and systems (buses, trains, bus or rail stations, parking areas, etc.) to continuously gather and provide information to travelers and transit managers (often via smartphones or displays). These systems embrace the hardware-to-software and connectivity competencies to coordinate between public and private transport, inform users of delays, streamline payment, and help plan and adjust routes (Gowtham & Mehdi, 2016; Neirotti, De Marco, Cagliano, Mangano, & Scorrano, 2014; Pelletier, Trépanier, & Morency, 2011). They support connectivity to various travel modes by communicating information about last-kilometer (last-mile) transport, creating facilities to accommodate other modes, and providing information for other modal needs. Like other smart transportation systems, the two-way communication capabilities within smart public transit allows infrastructure managers to continuously respond to demand conditions, for example by deploying additional buses if needed or directing users towards less congested areas (Smartcity, 2017). Users benefit from smart public transit systems through more convenient, reliable transportation.

Autonomous vehicles of varying sizes may reduce energy consumption and roadway capacity needs by pairing vehicle size with corresponding demand (e.g., sending a two-seater car when a two-passenger trip is requested) and enabling an innovative vehicle ownership model. This modularity in sizing allows vehicles to more accurately reflect rapidly varying demand conditions, particularly by enabling ridesharing during congestion (e.g., combining five one-person trips into one five-person trip). Traffic conditions change over days, seasons, and years, resulting in expensive overdesign to fit an infrequent, worst-case scenario, or under-design that causes congestion. Autonomous vehicles may also mitigate this issue by reducing parking and connecting to public transit or other modes (Estep, 2018; Miller & Heard, 2016; MIT Technology Review Insights, 2017). These vehicles use the compatibility and connectivity competencies to connect to other transport modes and into information systems for ridesharing. Another autonomous, modular vehicle technology, the Pop.Up system, is proposed to operate as both a drone and a driving vehicle on land (Schiavullo, 2017). This enables the flexibility to travel independent of roadways during congestion conditions, sometimes without the need for takeoff and landing facilities (Nneji, Stimpson, Cummings, & Goodrich, 2018). Further, passenger air transport could in the future reduce needs for ground-level transportation infrastructure and roads.

For a conceptual layout of an agile and flexible roadway transportation system including these examples, see Figure 3.

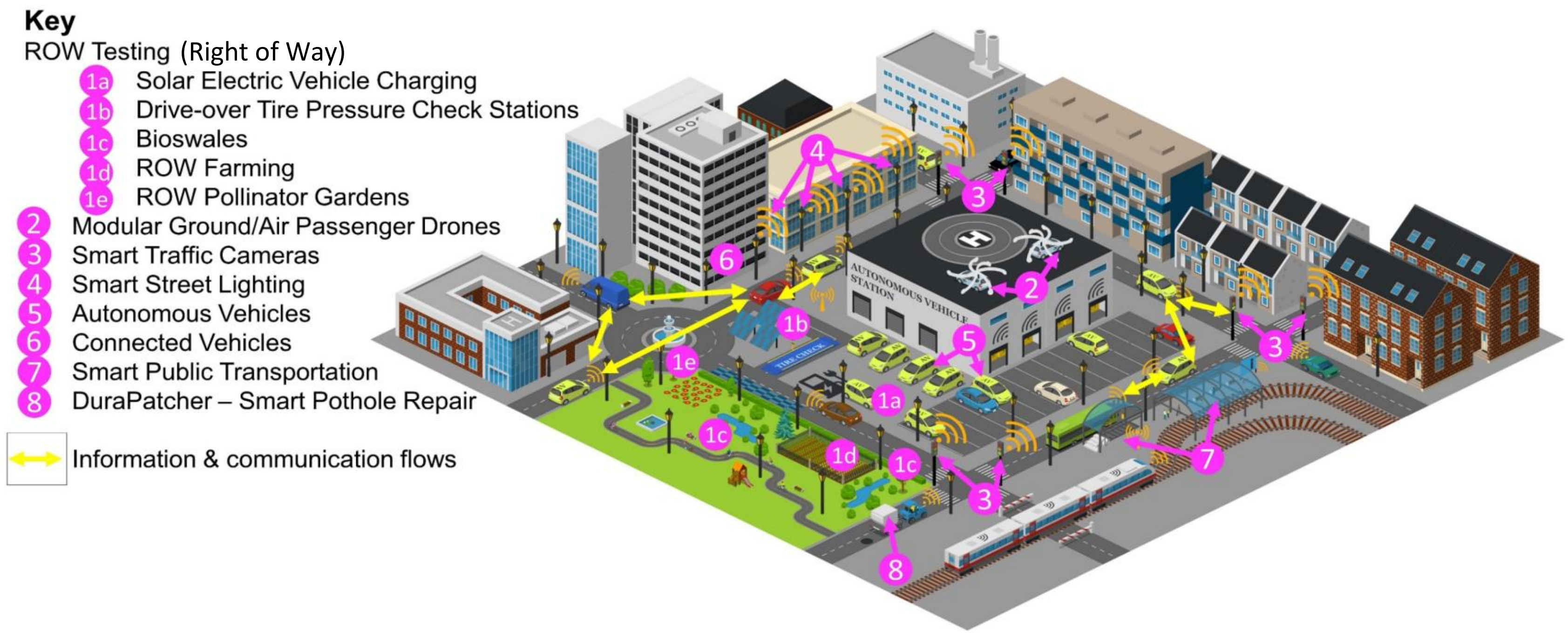

Figure 7: Future transportation network including smart systems and components.

Institutional Infrastructure

Institutions are the formal and informal rules that structure decision making by creating constraints, opportunities, and incentives (McGinnis, 2011; North, 1991). Institutions can be considered a form of infrastructure in that they provide a structure for the provision of public services and require investment to develop and maintain (Anderies, Janssen, & Schlager, 2016). Studies of water management systems show that institutions play a critical role in adaptive capacity (Halbe, Pahl-Wostl, Sendzimir, & Adamowski, 2013; Pahl-Wostl, 2009). Critically, physical and institutional infrastructure systems co-evolve so increasing the flexibility and agility of physical infrastructure requires investment in institutional infrastructure (Pincetl, 2016). Similarly to physical infrastructure, institutional infrastructure can exhibit complementary systemic properties like path dependency (Barnett et al., 2015; Kay, 2005).

Institution-related findings from this review emphasize the competencies of roadmapping, culture of change, and planned obsolescence, but cover all competencies across the board except modularity. These agile/flexible competencies share parallels with favorable features of institutional systems identified in a variety of disciplines. For example, the organic structure competency is comparable to polycentric governance systems described by policy and social-ecological systems scholars (Ostrom, 2010; Pahl-Wostl, Lebel, Knieper, & Nikitina, 2012). Similarly, the culture of change competency shares similarities with the concept of adaptive management in environmental and resource systems research (Schreiber, Bearlin, Nicol, & Todd, 2004; Walters & Holling, 1990). Recognizing that institutions play a considerable role in the form and function of physical infrastructure, this work includes examples of institutions directly surrounding several critical infrastructure systems. There is a rich and vast body of work in the area of institutional infrastructure that is outside the scope for this paper, which has been acknowledged but not incorporated here.

The Ray project in Georgia exemplifies the ‘continuous and reflexive experimentation’ and ‘learning by doing’ aspects of the culture of change competency in testing novel technologies in its right-of-way (Aupperlee, 2018; Clines, 2018). Though transportation system managers frequently test new technologies and practices, The Ray is uncommon in that it incorporates technologies that do not directly relate to transportation infrastructure. Its test projects include right-of-way solar power generation, pollinator gardens, and right-of-way farming in addition to tests to improve roadway performance. The Ray demonstrates transdisciplinary education in this respect, by operating across multiple sectors and being able to draw solutions from each. One article on The Ray project notes, ‘the biggest challenge ahead is shifting the direction of a 60-year-old industry where safety is the first priority, cost the close second, and sustainability nowhere on the list,’ (Boyd, 2016). Such innovation is critical in generating data and proving the value of new technologies to improve agility and flexibility both in transportation systems and urban systems at large.

In transportation infrastructure planning, the competencies of roadmapping, culture of change, and planned obsolescence have advanced transportation sustainability in the city of Curitiba, Brazil. In Curitiba, transportation planning is framed around the dynamic interaction of transportation and land use, continuous planning over time rather than one-shot efforts, and the value of access rather than of any particular transportation mode (Rabinovitch, 1996). Roadmapping is utilized in the creation of long-term plans for growth with less rigid land zoning. Planned obsolescence is embraced in two different ways: first, transportation plans are created explicitly with the mindset that they will need to be updated as conditions change, and second, outdated components are recycled as capital assets. Rabinovich and Hoehn (1995) summarize the planned obsolescence and culture of change mindset in Curitiba: 'The city had a "commitment to imperfection", by implementing whatever was possible at a certain point in time and later improving upon it.' As a result of these competencies, Curitiba enjoys an evenly distributed population density leading to lower congestion, effective and financially sustainable public transportation, and walkable streets (Rabinovitch, 1996).

Demand-side management applies the hardware-to-services competency to reduce infrastructure and new construction, by ensuring that needs are met not by increasing the provision of a resource, but increasing efficiency or minimizing its use (Guy, 1996; Guy & Marvin, 1996). For example, the city of Portland, Oregon reduced combined sewer overflows through measures such as green infrastructure to absorb stormwater, and disconnecting downspouts from stormwater pipe systems to reduce inflow (City of Portland Environmental Services, 2018). Another common example is the promotion of home energy use efficiency in electrical systems to limit stresses on aging power plant infrastructure, or to prevent construction of new power plants or additions to them (Strbac, 2008; USEIA, 2002). Efficiency measures, in contrast to built infrastructure, are less sensitive to uncertainties in environmental, economic, or demand conditions, potentially making systems that incorporate demand-side measures more resilient to such changes (risk-to-resilience) (Guy, 1996; Strbac, 2008). Reductions in demand (for Portland, through the services of increased infiltration and the impedance of runoff) are not susceptible to physical failure or infrastructure lock-in. Demand-side management can incorporate physical and institutional measures, but here are considered institutional because they are inherently about design of, policy around, and decision-making for infrastructure. Such measures reflect elements of the organic competency. Demand-side management recognizes that increasing the capacity of infrastructure to provide such resources will often be taken up by new development rather than serving existing needs and may even decrease flexibility (for example, Active Transportation Alliance, 2018; Feitelson & Salomon, 2000; Guy & Marvin, 1996; Sinha, 2003 in transportation infrastructure). This institutional practice can help conserve resources and allows flexibility in options for infrastructure managers when considering growing populations and needs.

The 100 Resilient Cities program, by the Rockefeller Foundation, seeks to institutionalize risk-to-resilience thinking in city government and infrastructure management, starting a resilience movement on a local scale and bringing it to global levels of influence. The organization collaborates with municipalities and brings multiple municipalities together to create a network of urban resilience knowledge and practices. Among its practices are inclusiveness of multiple disciplines and perspectives (transdisciplinary education), continuous monitoring and research to inform planning (culture of change and roadmapping), and using a distributed network of expertise and action (organic culture of experts). So far, the program has created almost 1,900 urban initiatives (Armstrong, 2017). The 100 Resilient Cities program recognizes future non-stationarity and its challenges in urban areas, and creates a flexible institutional structure to manage it.

In a more adaptable regulatory institution, temporary waivers from a regulation could be granted given an unexpected event without being stalled by linear or hierarchical decision structures that would undermine the readiness of response

(Pérez-Peña, 2002; Rossi, 1995). The roadmapping and planned obsolescence competencies could create measures in regulations that grant temporary waivers. Risk-to-resilience is also exemplified in the recognition of needs to adapt regulations to unforeseen circumstances. In post-disaster situations, regulations may restrict recovery efforts and are difficult to adjust. The Jones Act, also known as the Merchant Marine Act of 1920, was temporarily waived following Hurricane Katrina, Hurricane Rita, Superstorm Sandy, and Hurricane Maria, but the delay in the waiving process was blamed for shortages of necessary goods in the affected areas (Carey, 2017; Cope, Woosley, & Cope, 2018). Unplanned temporary waivers present issues also in that the push for a waiver may threaten the original regulation. For example, waivers of air quality regulations under the Clean Air Act were requested after the September 11, 2001 attacks to allow local transit authorities to recover; however, there were major concerns about the necessity of such a waiver and that the attacks were being used as an excuse to undermine the act (Pérez-Peña, 2002). Such temporary waiver measures in regulations may become more important as extreme events and extreme impacts from them increase under climate change.

Discussion

The major findings from this work include the benefits of systems with decentralized elements, and those with smart capabilities. However, these concepts need a critical examination to fully understand how such systems can provide adaptability, and to anticipate potential implications. A discussion of the competencies found in smart systems and in decentralized systems follows.

While decentralized, networked system structures often tended to align with agile and flexible competencies, the concept of decentralization should not necessarily be viewed as synonymous with agile and flexible. Examples of agile and flexible technologies tended to entail new organizational structures, particularly in terms of scaling and interconnectedness. Results suggested that existing infrastructure systems particularly around transmission, distribution, and conveyance infrastructure are unadaptable because they could not be easily changed or restructured. However, urban areas may be already locked in to these existing centralized infrastructure systems, and institutions are not likely to rapidly accept the major shift to decentralization. Therefore, semi-centralized or combined centralized and decentralized systems could be implemented more easily and help transition into a more adaptable infrastructure configuration (see Bouffard & Kirschen, 2008 in power systems; Porse, 2013 in stormwater systems; Zodrow et al., 2017 in potable water systems). Compatible components such as continuously-backwashing sand filters or battery technologies support such a transition. Thus, future systems may add on decentralized, networked components to add adaptability, without removing the benefits of existing centralized systems such as their maintainability and relative reliability of service.

Decentralization largely is supported by the modularity competency, through the ability to add components as needed without further changes in the system. In water and wastewater treatment infrastructure, an ‘economy of scope’ (efficiencies of variety rather than volume as in economies of scale) enables modularity, as this allows the scaling up or down of treatment processes. Treatment technologies such as hollow-fiber membranes and continuously-backwashing sand filters display this economy of scope. In electricity generation, modularity is supported by scalability, with renewable generation technologies that can be operated in a variety of sizes and locations (particularly solar panels and battery technologies). This modularity and scalability in water and electricity infrastructure also supports a combined central/decentralized system, and the ability to transition between the two configurations. Decentralized systems operate without the need for conveyance systems such as water distribution, wastewater collection, and power transmission infrastructure. These tend to be large structures with extensive rights-of-way and high path dependency (i.e., larger changes at the point of use may require changes at the point of service). They also can represent the largest portion of expenses in their respective infrastructure systems (Libralato et al., 2012). Decentralized components added to existing centralized systems can mitigate some of the path dependency and expense by offering the option to adapt via adding or removing either centralized or decentralized components.

A less centralized organizational structure supports the planned obsolescence competency through the removal of path dependency. Chester and Allenby (2018) noted, ‘infrastructure exists on such large scales that meaningful and timely changes may require herculean efforts.’ On smaller scales, such changes are facilitated. Components are less co-dependent, but can still operate with each other as a network via the connectivity and compatibility competencies (as in the case of virtual power plants), especially if combined with centralized components. Few of the physical infrastructure examples found directly utilize planned obsolescence as a strategy towards adaptability, possibly because of connotations with wasteful product design (see Acaroglu, 2018; Aladeojebi, 2013). Additionally, durable structures and systems are often perceived as the most sustainable and resilient (e.g. Kaminsky, 2015; Mirza, 2006). This is not to say that components of decentralized systems should not be durable; the planned obsolescence competency arises from the organizational structure of the infrastructure, not from the durability of the components.

In decentralized infrastructure the risk of failure is distributed differently from low-probability, high-consequence to higher-probability, lower-consequence events (for similar concepts in other applications see Arcuri & Dari-Mattiacci, 2010; Schmitt, Sun, Snyder, & Shen, 2015). Major environmental stressors such as hurricanes are more likely to damage components, but each failure results in a much smaller loss of service. In this way, risk is distributed more broadly, similar to how diversifying investments in financial decisions results in greater security. For example, modules in water/wastewater treatment (e.g. hollow-fiber membranes) or power generation (e.g. container microgrids) can be used almost anywhere and therefore are more accessible, making recovery easier. A system with aspects of both centralized and decentralized components and networks incorporates the risk distributions of both, allowing differently scaled responses to stressors and a higher degree of system level redundancy (Ahern, 2011).

Smart technologies have a variety of applications and implications in adaptable infrastructure. The hardware-to-software, connectivity, and compatibility competencies bring sensing, response, and information services to infrastructure components (e.g., smart traffic signal cameras). As in electrical power systems, connectivity and compatibility appeared collectively in, and as a defining characteristic of, smart adaptable infrastructure. Together these two competencies allow infrastructure to operate across other infrastructure, management systems, and users. In general, infrastructure that are both smart and adaptable have two-way communication capabilities. Sensing and monitoring allow rapid detection of changes in, for example, electricity demand (e.g., smart battery systems) or roadway conditions (e.g. connected vehicles). Then, the two-way communication ability allows an immediate response, for example, for automatic and remote configuration of the infrastructure (e.g. virtual power plants) or messages to infrastructure managers or users (e.g. mobile flood identification apps). In general, smart infrastructure uses ICT systems to become proactive rather than reactive to changes in demand or environmental conditions.

Smart systems, however, are not inherently adaptable and infrastructure using them may take on new vulnerabilities. Rigid, risk-based control structures may be built in to the software surrounding smart systems. ICT-connected systems take on vulnerabilities from cyberattacks, interdependencies with other infrastructure (e.g. electricity and ICT implemented in vehicles, stormwater management, traffic control, etc.), and complexities. Geopolitical security and cyberattacks are expected to be an increasing concern worldwide as smart technologies grow (Chester & Allenby, 2018). In one recent case, a casino was hacked through its Internet of Things-enabled fish tank thermometer (Wei, 2018). Again, this research does not attempt to present ICT-enabled infrastructure as a panacea, and future research should thoroughly evaluate these vulnerabilities and develop mitigation strategies as such technology is applied broadly to infrastructure.

For agility and flexibility at large, the two-way communication and response capabilities of ICT and smart systems engender adaptive capacity over the short term, where the restructuring and updating capabilities of decentralized infrastructure are long term. Further, smart technologies improve infrastructure at the component level while decentralized, networked structures add adaptability at the system level. Together, smart technologies and systems with decentralized structures complement each other to enable an overarching paradigm of adaptivity. This is not to say that smart and/or decentralized components and systems are the only paths to adaptive capacity; additional strategies may be uncovered in future research.

Finally, it appears that there is some degree of overlap between climate mitigation and response efforts. This appears in electrical power systems (renewable energies seem to be more adaptable than fossil fuels or nuclear) and water (wastewater reuse can be more adaptable than releasing treated wastewater; green infrastructure can be more adaptable in managing stormwater than pipe systems). This is likely a positive result, showing that infrastructure managers may not have to compromise environmental sustainability for resilience to climatic and other changes.

Empirically tested examples are especially important in showing the effectiveness and functionality of the ten competencies and the concepts for agility and flexibility proposed here (for one empirical example see Cardin, Bourani, & de Neufville, 2015). Economic and cultural context, as well as many other factors, are important in determining the effectiveness of these technologies and examples in any given area. Potential concerns around novel infrastructure systems and components include economic costs, social effects such as gentrification (especially in the case of green infrastructure), or rare material requirements (e.g. large batteries) within the life cycle of building and managing such systems. In particular, institutional infrastructure need more robust research, as it often dictates the form and functionality of physical infrastructure. Future physical and institutional infrastructure research should address the large-scale, long-term effects of such concerns, especially given a non-stationary future.

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