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Toward indicators of the performance of US infrastructures under climate change risks

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Abstract

Built infrastructures are increasingly disrupted by climate-related extreme events. Being able to monitor what climate change implies for US infrastructures is of considerable importance to all levels of decision-makers. A capacity to develop cross-cutting, widely applicable indicators for more than a dozen different kinds of infrastructure, however, is severely limited at present. The development of such indicators must be considered an ongoing activity that will require expansion and refinement. A number of recent consensus reports suggest four priorities for indicators that portray the impacts of climate change, climate-related extreme events, and other driving forces on infrastructure. These are changes in the reliability of infrastructure services and the implications for costs; changes in the resilience of infrastructures to climate and other stresses; impacts due to the interdependencies of infrastructures; and ongoing adaptation in infrastructures.

Keywords Climate change · Indicators · US infrastructures · Reliability · Resilience · Interdependencies · Adaptation

1 Introduction

Kenney et al. (2018) in this Special Issue propose using indicators to provide an ongoing assessment of the state of climate change impacts on important US economic and natural sectors as a means to support a sustained US National Climate Assessment (NCA). The National Climate Indicators System (NCIS) identified built infrastructure as a topic of interest for inclusion in the system (Kenney et al. 2018; Kenney et al. 2016: Buizer et al. 2013; Kenney et al. 2014). Built infrastructures

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are among the most prominent systems impacted by many kinds of climate-related extreme events, and are comprised of the buildings we live and work in, and our communication, transportation, energy, and water systems (examples are Schweikert et al. 2014; Abdrabo and Hassaan 2015; Hayhoe et al. 2010; Chappin and van der Lei 2014; Panteli et al. 2015; Douglas et al. 2017; Moss et al. 2019; Koliou et al. 2020). Being able to monitor the impacts of climate events on these infrastructures is of critical importance to help address questions about the degree of impacts and potential responses to protect infrastructures and their services.

Kenney et al. (2018) describe issues of importance to the NCA. Are these infrastructures more or less vulnerable now due to changes in the climate system than in the past? Are they becoming more vulnerable as we look toward the future? Are upkeep, upgrades, replacements, and other interventions keeping pace with and preparing us better for a future which we know will be characterized by increasingly severe and frequent climate extremes? Here, we present candidate indicators that might be used in an ongoing assessment of the state of US infrastructure under a changing climate that Kenney et al. (2018: pp. 3–4) describe in terms of five criteria: "those sectors or topics previously included in one or more of the NCA. . . indicators needed to be justified by a transparent model of how each system is structured and how it functions. . . indicators needed to have a documented relationship to climate change and variability. . . indicators must correspond to phenomena that are of national importance . . . indicators ought to be used" for policy and investment.

1.1 Climate-related aspects of infrastructure for indicator development

Four aspects of infrastructure under changing climate conditions are considered in order to address the development of a system of impact indicators: (1) changes in the reliability of infrastructure services and their associated cost implications, (2) changes in the resilience of infrastructures to ongoing changes in climate and other stresses, (3) infrastructure interdependencies that are inherent properties of infrastructure networks, and (4) ramifications of adaptation actions and effects of moving infrastructure toward less vulnerability. These indicators are applicable to most, if not all, types of infrastructure systems.

The terms reliability, resilience, infrastructure interdependencies, and adaptation are defined differently yet are also interrelated. Reliability refers to the ability of an infrastructure to achieve a certain level of performance, usually measured against some standard, and encompasses other concepts such as effectiveness and availability (National Research Council 1996). Resilience is the ability to withstand stress and is often characterized as the ability to return to some equilibrium point, which is either the same as before or at some more resilient level, i.e., the capacity to "bounce forward" (Zimmerman 2016; Borenstein 2014; Vale 2014). Interdependencies refer to interconnections among infrastructures in multiple directions (Rinaldi et al. 2001). Adaptation has been defined in a number of ways, and in the Fourth National Climate Assessment, it is defined as a form of risk management as follows: "Adaptation refers to actions taken at the individual, local, regional, and national levels to reduce risks from even today's changed climate conditions and to prepare for impacts from additional changes projected for the future" (Lempert et al. 2018: Introduction, citing Easterling et al. 2017, Hayhoe et al. 2017, Vose et al. 2017, and Wuebbles et al. 2017).

Indicators to measure changes in these four areas over time are valuable to capture the more dynamic aspects of the impacts, a critical need identified by Sharifi (2016). Two of the four areas, namely resilience and adaptation, are presented here as illustrative of the extent of climate-related indicator development. For *resilience*, climate change indicators have often been applied. For example, the National Institute of Standards and Technology (2014) has undertaken an indicator orientation to resilience in a number of infrastructure sectors as has the US Environmental Protection Agency (2017). The US Department of Homeland Security (2017) has identified a number of resilience-oriented indicators and presents them in the form of definitions and applications for sector-specific reports, many of which are infrastructure-related. Many reviews of the definition and dimensions of resilience exist (Sharifi 2016). The Sharifi (2016) review and evaluation of 36 resilience community assessment tools, many encompassing infrastructure, identified a series of frequently observed weaknesses in the structure of the tools (including being able to take into account environmental indicators, dynamics over time and across space, iterative process, and uncertainties). Koliou et al. (2020) focus on the broader topic of community resilience which extends to include indicators of the ability of a community to resist, absorb, and recover from infrastructure failures. The paper reviews initiatives; definitions in engineering, sociology, and economics; and research and gaps in several key areas. These include system interdependencies, buildings and critical infrastructure, lifeline systems (power, water/wastewater, natural gas, transportation), social systems, and economic systems. Some of the research gaps identified include developing a framework for a “systems of systems” approach (which are covered in Section 3.3 using a different language, i.e., interdependencies). The review touches on gaps in coverage of substantive issues, as well as other gaps such as integrating engineering and economic models to estimate impacts on social and economic systems, improving understanding of recovery time scales for lifelines, looking at intermodal transportation systems, accounting for household to community to regional scales of social impacts, and fuller evaluation of recovery pathways using economic analysis.

Adaptation-oriented indicators also have been developed worldwide from promising risk-oriented approaches that use options that are both structural and non-structural. A few examples are the Urban Sustainability Directors Network (2016) general guide for cities on developing urban climate adaptation indicators and the Climate ADAPT Urban Adaptation Support Tool that provides a compiled set of monitoring indicators from cities using them in their adaptation planning or developed by research institutions or used in national frameworks (https://climate-adapt.eea.europa.eu/knowledge/tools/urban-ast/step-6-3). ND-GAIN has developed an urban adaptation assessment indicator list found at https://gain.nd.edu/assets/256491/new_uaa_indicator_list.pdf and the National Institute of Standards and Technology (NIST) has produced the “Framework for Defining and Measuring Resilience at the Community Scale: the PEOPLES Resilience Framework” (Renschler et al. 2010).

1.2 Selected challenges to aggregated climate-related infrastructure development

Wilbanks et al. (2013) in their technical report in support of the National Climate Assessment identified a number of formidable challenges in developing integrative aggregate indicators of the implications of climate change for US infrastructures. These are presented below as Wilbanks et al. (2013) identified them.

First is the high degree of variability in the definition of the term “infrastructure,” which is defined in numerous ways, even though the customers and resources are often shared. For example, as indicated in Wilbanks (2017: 11), sixteen sectors were identified in Presidential Policy Directive 21 of February 2013 (PPD21) (White House 2013) that did not correspond to those identified by the American Society of Civil Engineers

(ASCE, subsequently discussed) as report card sectors, and each of the sectors varies with respect to the kinds of institutions that would incorporate climate change.

Second, the indicators across infrastructures are often not widely accepted or validated and have focused more on environmental conditions and less upon climate change (see as example Schelling 1992, and discussion of infrastructure in International Panel on Climate Change 1992). Multiple and compounding stresses can exacerbate climate change effects.

Third, over and above physical characteristics of infrastructure are concerns about service values and supply chain disruptions that compound such losses (some examples are provided by Upakhyaya et al. 2014; Jaroszweski et al. 2010; Ruth 2010). Infrastructure services include productivity, mobility, convenience, and comfort, all of which are vulnerable to impacts of climate change in many ways.

Fourth, the interconnected nature of many infrastructures poses special issues in terms of the management, the operation, and the research supporting such connections (Zimmerman et al. 2019; Wilbanks et al. 2013; Kirshen et al. 2008; Rinaldi et al. 2001, Chappin and van der Lei 2014, Chopra and Khanna 2015, Sebastian et al. 2017, Intergovernmental Panel on Climate Change 2012 and US Global Change Research Program et al. 2018a). Many interconnections are not well enough understood for the incorporation of indicators though some progress is being made.

Most of the integrative attention to infrastructures to date has been in an urban context. In fact, the two topics—urban and infrastructure—are often combined (e.g., US Global Change Research Program 2014; US Global Change Research Program et al. 2018b; Wilbanks and Fernandez 2012/2014; Wilbanks 2017; Cutter et al. 2014). As Wilbanks and Fernandez (2012/2014) have noted, extensive literature exists that exemplifies the reduction in vulnerabilities using adaptation strategies in urban areas (e.g., City of New York 2013; Boston 2016; Chicago 2008 and updates). Adaptation strategies present their own important set of infrastructure indicators as applied in urban areas that include establishing baselines, tracking progress toward adaptation goals, and evaluating effectiveness.

1.3 Examples of indicators in infrastructure sectors

Among the individual sectors, the *transportation* sector has stood out in its attention to climate change implications and in some cases indicators as well. A path-breaking study in considering implications of climate change for an infrastructure sector was the Transportation Research Board (TRB) (2008). CCSP SAP 4.7 (2008) continued this tradition for a particular area, the US Gulf Coast. The Federal Highway Administration in 2012 developed a vulnerability assessment framework and pilot program (FHWA 2012), and two pilots experimented with the use of indicators (Rowan et al. 2014). The National Climate Assessment has similarly routinely used climate change indicators for transportation as well as other infrastructure sectors (Jacobs et al. 2018).

An example of similar studies in other sectors is for *water* systems, such as stormwater sewers (Van der Tak et al. 2010), many of which have considered indicators of vulnerabilities to climate variability and/or projections of climate change. The water sector has considered indicators of stresses, generally related to ratios of changes in water availability versus changes of water consumption such as CESR's Water Exploitation Index (CESR 2009) and MIT's Water Stress Index (Schlosser et al. 2014). Considerable attention has been paid to indicators of stress on waste management systems in the context of sustainable development (e.g., Hammond et al. 1995).

The *electric power* sector components have often been evaluated in terms of general climate change indicators (US Department of Energy 2013a) in the context of weather extremes such as hurricanes (US Department of Energy 2013b), and across the entire energy supply chain (Aivalioti 2015; Rolnick et al. 2019). Other references for the energy sector are addressed in Section 3.2.

Despite the above efforts for individual infrastructure sectors, indicators for infrastructures must be considered an integrative, ongoing developmental activity, and our four priority areas provide support for that. For example, the Infrastructure Subcommittee of the Office of Science and Technology Policy (OSTP) Homeland and National Security Committee in 2012 concluded that improving the capacity to define and monitor infrastructure resilience is a very high national priority along with a number of other activities directly related to indicators of threat exposure, vulnerability, and adaptive capacity (also see previously referenced PPD21). The National Institute of Standards and Technology (2014) found that in many cases indicators of the status of infrastructures with respect to climate and other stressors are in their infancy, and satisfactory data sources do not exist (see also Avery et al. 2018).

2 Conceptual model of infrastructure indicators

Conceptual models of climate change implications for built infrastructure extending across the range of individual sectoral infrastructures in terms of the four priority areas addressed here are not widely available. Based considerably on a national workshop of leading infrastructure experts, Wilbanks et al. 2013 summarized the knowledge base as follows citing an earlier Oak Ridge National Laboratory report: "Cross-sectoral issues related to infrastructures and urban systems have not received a great deal of attention to date in research literatures in general and climate change assessments in particular." Kenney et al. (2014), building on the work of Wilbanks et al. 2013, underscored the need for infrastructure conceptual models and suggested an initial framework in their "Pilot Indicator System Report." This emphasis on infrastructure and cross-sectoral impacts has continued through subsequent versions of the National Climate Assessment by the infrastructure sector (US Global Change Research Program et al. 2018a).

Figure 1 depicts how indicators can cut across different aspects of infrastructure systems. The provision of infrastructure services is shaped by a number of climate and non-climate factors, including human actions (e.g., increased personal vehicle usage, energy consumption, water demand, digital communication, pesticide and pharmaceutical loadings to wastewater) that may be placing demands on infrastructures that are beyond their design capacities. The stressors also include factors that influence the supply services of infrastructure systems such as streamflow and air temperature. These stressors, in turn, influence vulnerabilities that can be measured by changes in resilience, reliability, and interdependency impacts. For example, for interdependencies, services from any one infrastructure are often imbedded in interdependencies with other infrastructures, such as energy relationships with water and communications infrastructures. Finally, infrastructures need to limit adverse effects of climate change impacts on services, which require adaptation that is iterative and responsive to feedbacks that change as stressors and vulnerabilities change.

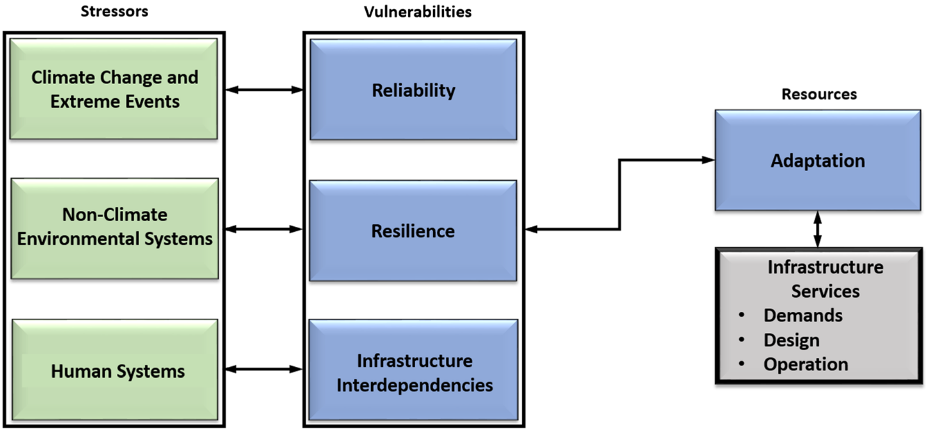

Fig. 1 Conceptual model for infrastructure indicators

3 Toward a comprehensive set of infrastructure indicators incorporating climate change

Infrastructure is, in a sense, the physical scaffolding (akin to the skeleton, circulatory system, and nervous system of a body) for human and human-managed systems, and so it is not surprising that its components and their interplay are related to a wide range of forces working across the spectrum of national indicators. Particularly close are indicators for energy services and mitigation, e.g., greenhouse gas indicators related to emission policies. Also important are the global context (atmospheric air temperature, sea level rise, the rate of climate change and extremes), indicators of local water temperature and availability and ecosystem services, and oceans/coastal indicators related to shipping and ports. Some indicators, however, relate to sensitivities of infrastructures themselves to climate change, and capturing these is our objective here.

As mentioned above, research has not generally focused on climate change impacts across infrastructure sectors. Discussions have been informed by studies on sectors mostly in the purview of public sector entities (especially for transportation and cities: see Section 1.3 above), the private sector (e.g., Schiff et al. 2013; SwissRe 2014, 2015a, 2015b), and their responses to disruptive events. A number of consensus reports on cross-sectoral impacts have begun to emerge from government, private sector organizations and NGOs, and academic experts summarized in Wilbanks et al. 2013 and later by the US National Climate Assessment reports, among other sources.

We introduced in Section 1.1 four priorities for climate-sensitive infrastructure indicators and these are related to (1) reliability, (2) resilience, (3) interdependencies, and (4) adaptation. All of these priority indicators will require data to support them, little of which are available at the moment, as well as clarification of concepts and models to help generate them. We assess each of the four priorities in the following sections. Assessments of infrastructure service changes in light of climate change require the holistic perspective that these four priority areas begin to provide. The indicators must also span systems, geographies, and time, and show how they are shaped by investment and policy changes.

3.1 Indicators of changes in the reliability of infrastructure services and cost implications

Measures of infrastructure service outages are a common indicator of changes in reliability through time, although the driving forces behind outages often include factors other than climate effects alone (e.g., Münzberg et al. 2014). Outages can occur from equipment damage or blockages, or voluntary shutdowns to avoid equipment damage, and some cost estimates to utilities and customers have been developed (e.g., Congressional Research Service 2012). Among advanced work on developing indicators of performance under stress is ongoing work in the electric power sector. For instance, a 2015 IEEE paper reports efforts to develop key performance indicators (KPI) such as transmission delays, and Quality of Service (QoS) indicators (Onyemeh et al. 2015) related to very stringent stability requirements for smart grid systems.

As Kenney et al. (2014: B-50) observe, major infrastructure disruptions are sometimes supported by some emergency response agencies such as the Federal Emergency Management Agency (FEMA) and disruption costs are often kept by insurance agencies. However, comprehensive or consistent databases on outages linked to causes are still needed.

A few examples illustrate the damages to infrastructures and their reliability that occur repeatedly during exposures to extreme events where the consequences are similar or analogous to those that can be expected from climate change. Hurricanes Irene and Sandy exemplify the extent of infrastructure damage that can occur in severe weather events. Across the transportation, electric power, and water infrastructures, closures were both preemptive and occurring from rain, flood, and wind damage. During Hurricane Irene in 2011, road closures were extensive, amounting, for example, to at least 2400 in Vermont alone, 350 in New Jersey (NJ), and 270 in North Carolina (US Department of Commerce National Oceanic and Atmospheric Administration National Weather Service 2012). Electric power outages were estimated at $8 million (US Department of Commerce National Oceanic and Atmospheric Administration National Weather Service 2012). A few months after Hurricane Sandy in October of 2012, NOAA cited damages to the NJ roadways, bridges, and transit worth $2.9 billion (Blake et al. 2013). In New York City, damages to the subway system were estimated at $5 billion, plus $2.5 billion for the remaining NY transportation infrastructure (Blake et al. 2013).

In order to identify priorities and needs for investment and overall strategic planning and risk management, Kenney et al. (2014: B-50) suggest as an indicator the annual US Disaster Declarations used by FEMA beginning in 2002 and decadally since 1982. FEMA data show peaks in 2005 and 2011 (FEMA 2020, http://www.fema.gov/disasters/grid/year). One useful approach would be to distinguish outages reflecting climate change and/or climate-related extreme events.

The American Society of Civil Engineers (ASCE) periodic infrastructure report card, described below, could also provide indicator information related to infrastructure reliability.

3.2 Indicators of changes in the resilience of infrastructures to climate and other stresses

It would be very useful to be able to monitor by region and type of infrastructure a measure of changes in the current resilience of the infrastructure (e.g., National Research Council 2012; National Institute of Standards and Technology 2014; National Academies 2017). This would also include the coping capacity of institutions to respond to and recover from infrastructure disruptions such as the ability to assemble and manage resources within time frames associated with extreme events, to mobilize social networks to support community problem-solving, and to represent community values in developing strategies for longer-term recovery (Aldrich 2010; Aldrich and Meyer 2015; Zimmerman 2016). Important to understanding resilience also would be knowledge of where thresholds exist in infrastructures related to their underlying conditions and the type and severity of climate change impacts to assess when infrastructures might fail and how to make them more resilient. As Kenney et al. (2014: B-50, 51) observe, the term "resilience" "has become a widely used term, connoting positive accomplishments in contrast to negative connotations of 'vulnerability,' and that efforts to propose definitions and metrics have also emerged" and they cite as examples Cutter et al. (2008), Wilbanks and Kates (2010), and Vugrin et al. (2010). Since that time, other definitions have arisen such as those by the National Research Council (2012), Sharifi (2016), and Koliou et al. (2020). Kenney et al. (2014: B-51) note further some limitations: "potential users of such metrics – such as public and private finance and insurance decision makers – do not yet see metrics that are robust enough to serve as a basis for resource allocations." They also identified the efforts of the Infrastructure Subcommittee, Homeland and National Security Committee of OSTP that met in 2012, and agreed that resilience measures and their evaluation were essential priorities for US "R&D priorities for improving capacities to answer high-priority national infrastructure questions." Yu et al. (2020) argued for an alternative to focusing on the component-specific resiliency of infrastructure to one that incorporates a broader view. That perspective would consider context, a socio-ecological perspective, complexity, connectivity, diversity, adaptive capacity, social capital, among other factors.

The condition of infrastructure is often an underlying or contributing factor in infrastructure resilience. The argument is that if infrastructure is already in poor condition, it will be more vulnerable to hazards of any kind, in particular, climate change, and interconnections among infrastructure systems (addressed in Section 3.3) as well as infrastructure interactions with the environment will exacerbate these impacts. The American Society of Civil Engineers (ASCE) periodic report card for sixteen infrastructure categories is an often-cited barometer for infrastructure condition, though a number of infrastructure-specific condition reports exist as well, most notably for transportation, dams, and electric power. The assessments in the ASCE report cards are based on consensus judgments of groups of engineering professionals.

As Kenney et al. (2014: B-52) describe, infrastructure condition sector by sector is graded by ASCE as a letter drawing upon both quantitative and qualitative characteristics conducting 4-year national assessments and more frequent ones at state levels and infrastructure sectors. The most recent report cards in the twenty-first century were issued in 2005, 2009, 2013, and 2017.

Kenney et al. (2014: B-51 and B-52) point out that in order to measure infrastructure condition, the American Society of Civil Engineers (ASCE) in the report cards it issues rates infrastructure as follows: "grades are based on eight criteria (capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation). A is defined as exceptional, B as good, C as mediocre, D as poor, and F as failing." In the 2017 ASCE report (ASCE 2017), the grades for 16 infrastructure categories ranged from D− for various water infrastructure categories to C+ for solid waste management. America's infrastructure average grade was a D+, when in prior years it averaged D. The total investment needs were estimated at $4.6 trillion to 2025 (2015 $s), increasing from estimates in earlier ASCE report cards of $3.6 trillion by 2020, $2.2 trillion in 2009, and $1.6 trillion in 2005 (ASCE 2017).

Kenney et al. (2014: B-52) also note that ASCE gives investment need estimates based on a criterion of achieving a grade of B or better. The fact that the reports are based on judgments by groups of experts can be considered a strength, but for national indicators, they are limited by the fact that they may not easily be measured and replicated by others.

Indicators of resilience have been attempted for stress and change for individual sectors; these are a foundation for integrating them in Section 3.3 on interdependencies. Several of these individual infrastructure sectors are introduced and described briefly here. Efforts to develop indicators of *transportation* sector vulnerability and resilience (e.g., Rowan et al. 2014) resemble those in community resilience (National Research Council 2012; Cutter 2015; Sharifi 2016), i.e., developing a detailed taxonomy of individual components of resilience that can be estimated from available data sources—an approach that has so far not led to satisfactory aggregate metrics. These components include a variety of useful partial indicators, such as reductions in clearance under bridges and monitoring improvements in technologies and materials (TRB 2008), transportation facilities subject to inundation by a specified level of flooding or storm surge, and trends in short-term flooding (Climate Change Science Program (CCSP) 4.7 2008). Jacobs et al. (2018) present an extensive set of transportation indicators related to climate change, and Markolf et al. (2019) similarly present transportation indicators in the context of sustainability. Two case studies of urban resilience to climate change were recently conducted, using indicators for eight municipal management sectors (US Environmental Protection Agency 2017).

The application of climate-related indicators for the *water* sector was discussed in Section 1 and originates from government, academia, and professional societies and organizations. They include water stress and exploitation indexes and are applied across the board from water sources through wastewater management.

Similarly, indicators that are climate oriented have been developed for the *electric power* sector (Bartos and Chester 2015; Aivalioti 2015). The US Department of Energy (2013a) applied such a set across many components of climate change at the level of individual electric power infrastructure components. Many such indicators arise in the context of specific extreme events such as hurricanes as well at component-specific levels for the electric power sector (US Department of Energy 2013b). Energy demand or consumption is a foundation for understanding climate factors. Wachs and Singh (2019) outlined estimates of these demand factors using the State of Indiana as an application area. Yalew et al. (2020) have reviewed an extensive literature—220 studies—that address energy and climate relationships at multiple geographic scales, as well as developing a model for energy planning that takes these relationships into account.

A common resilience theme among many indicators that cuts across the four priority areas is time of recovery of an infrastructure from a failure. These are described and applied in Section 3.3 for infrastructure interdependencies and could also be applicable as a source for resiliency indicators for single infrastructure systems as well.

3.3 Indicators of infrastructure interdependencies

A considerable literature characterizes interconnectivity among networked infrastructures as bidirectional interactions and dependencies as acting predominantly in one direction (Rinaldi et al. 2001). Familiar examples include the dependency of communication infrastructures on energy infrastructures and the dependency of energy infrastructures on water infrastructures Wilbanks et al. 2013. A specific example is Hurricane Harvey that brought wind, storm surge, heavy precipitation, and floods to the Houston area that resulted in direct impacts such as flooded homes and crippled municipal water systems, and raised concerns about basic sanitation as well as secondary effects of uncontrolled chemical fires and environmental contamination (Sebastian et al. 2017). Interdependencies have been introduced in terms of the "systems of systems" context (Udaya and Maraisa 2014; Ferrario et al. 2016). Climate-related impacts can cascade not only from one extreme event to another, such as electricity outages during a heat wave, but also from one infrastructure to another.

Network theory lends itself well to articulating indicators for interdependencies. For example, an indicator could be developed that would measure the size and number of critical subnetworks connecting infrastructure layers Wilbanks et al. 2013, where the loss of one component means that critical functions cannot be served. Indicators of interdependence are not as obvious in the literature; however, a number of indicators based on network attributes are possible as some recent research suggests. Bashan et al. (2013) underscore the fact that even small changes in interdependent infrastructure networks can produce large catastrophic failures, which suggests more novel indicators for interdependent infrastructures. Ferrario et al. (2016) apply models to portray networked aspects of interdependent infrastructures (as systems of systems). Ouyang (2014) reviewed an extensive series of modeling approaches for interdependent infrastructures, many of which incorporate indicators of the interdependence phenomena.

Another approach would be to define a matrix of critical infrastructures and their interdependencies on one another that, for each element, would show the "recovery rate": the ratio of the amount of time a dependent infrastructure facility takes to recover relative to the time it takes the infrastructure upon which the main infrastructure is dependent recovers (Zimmerman and Restrepo 2006). Recovery rate is estimated by the US Department of Energy (DOE) for electricity system components relative to impacts of extreme events (e.g., US DOE 2013a, 2013b). Zimmerman (2014) applied the recovery rate concept to transit and electric power following Hurricane Sandy with the two types of infrastructures being implicitly interdependent. Zimmerman (2016) applied numerical recovery rates to selected power plants in the USA following a variety of disruptions of which many are typical of climate change impacts. Sharkey et al. (2015) also examined the value of information sharing in addressing infrastructure restoration through the lens of interdependencies. Haggag et al. (2020) conducted an extensive meta-analysis of infrastructure interdependence drawing upon the literature on recovery and restoration above, and resilience metrics assume a central place in the analysis.

3.4 Indicators of ongoing adaptation in infrastructures

Another set of useful indicators would focus on adaptations in infrastructures in response to concerns about climate change impacts. These provide important resources for sustaining infrastructure services. They are potentially adjustable as the stressors and vulnerabilities change as portrayed in Fig. 1. They also shape new directions for infrastructure services toward being more reliable, resilient, and sensitive to the impacts of interdependencies. Although most adaptations seek benefits beyond climate change management alone, it would be informative and instructive for national indicators to track changes over time in the nature and rate of infrastructure adaptations that can be attributed in substantial part to experience with or concerns about climate change risks: either changes in operational practices or changes in capital stock. It must be noted, however, that just because adaptation has been undertaken does not assure that present and future performance will be improved. As noted in Section 1.1, indicators have been recently developed for adaptation based upon promising approaches for risk management from a number of innovative initiatives in US cities and in other countries. Two types of adaptation measures are addressed below related to operational changes and capital investments.

3.4.1 Changes in design criteria, codes, standards, and other practices that affect infrastructure operation

Regarding climate- and weather-related design criteria for infrastructure systems, which differ by infrastructure and threat (e.g., flooding, drainage), TRB 2008 has pointed out that it would benefit stakeholders and decision-makers to have data on changes in (a) when criteria are exceeded by location, over time, how long, and intensity; (b) changes in criteria values over time (e.g., re permafrost in Alaska); and (c) changes in codes, standards, and other regulations that reflect such criteria (TRB 2008). The fact that codes or standards have been changed in response to climate change risks is an important indicator, even if the impacts of the changes remain to be evaluated. These are tangible, measurable variables.

In cooperation with such professional groups as the American Society for Civil Engineers (ASCE), it should be possible to develop indicators of these types, which are closely related to ASCE's national infrastructure report card activities. A further consideration in an ASCE White Paper (ASCE 2013) incorporated benchmarks in the form of standards and criteria as well as procedures to include the environment and detection systems. Examples of topics of special interest might include (a) the degree to which flexibility is an aspect of infrastructure design, implementation, and operation, e.g., in definitions of engineering standards, and (b) measures of adaptive risk management practice by type of infrastructure and type of threat. In a subsequent White Paper (ASCE 2015), ASCE recommended adaptive strategies such as conservative minimum design criteria, using a low-regrets approach, to improve building performance when exposed to extreme events and climate change.

Some such adaptive actions are being taken in individual locations and sectors. For example, the Boston Water and Sewer Commission is switching its precipitation design conditions from a 1960 assumption that a 10-year storm has 4 in. of precipitation to a 2013 value of 5.2 in. (BWSC 2013). The City of New York has adopted a policy requiring in a specific region the elevation of new construction above designated flood levels based on how future sea level rise is projected defined by the New York City Panel on Climate Change as well as improving the City's infrastructure resilience and the built environment overall by means of numerous local laws and programs (Solecki and Rosenzweig 2014). The City of New York (2013) has also evaluated its wastewater and stormwater systems at the component level against estimated flood levels as a basis for selecting alternative adaptation measures to prevent damage from sea level rise. Whether these will be translated into code changes or design and operational practices is to be determined. Similarly, Van der Tak et al. (2010) report proposed changes in stormwater design criteria in Alexandria, VA, to incorporate climate change observations and projections. A methodology has been developed for determining "nuisance flood elevations," catalyzed by the New York experience, which could be applied in a national indicator based on a sample of coastal sites that would indicate changes through time in exposure to sea level rise (Sweet et al. 2014).

Electric utilities self-report violations of North America Electric Reliability Corporation Critical Infrastructure Protection (NERC CIP) standards, and regulatory commissions often require reporting of changes in functional performance specifications (Kenney et al. 2014: B-

21; Wilbanks et al. 2013 13). Otherwise, practices are mainly tracked by professional organizations such as ASCE and by institutions' training engineers and managers for infrastructure-related careers. It should be possible, however, to start with indicators of emerging change in design criteria, standards, and practices by location and sector across the nation which are perhaps related to such exposure/impact data as NOAA's regularly updated estimates of extreme precipitation events: http://www.nws.noaa.gov/oh/hdsc/currentpf.htm .

3.4.2 Changes in investment in infrastructure turnover/replacement/revitalization

Although causal factors are diverse and climate change is seldom a major driver, except for major extreme events, it would be useful to be able to observe, by region and type of infrastructure, what the replacement, revitalization, and capital stock turnover rates are for local infrastructures, and their concomitant implications for resilience to climate change.

The rate of change in built infrastructures is a measure of opportunities to mainstream climate change risk reduction in infrastructure capital stock replacement. Industry sources indicate that a substantial portion of many infrastructures are either replaced or revitalized over a period of 30 years, depending partly on the availability of funding and partly on such other driving forces as the incidence of disruptive events. This pace can be either accelerated or decelerated depending on market, policy, and technological driving forces. An indicator of either the magnitude of infrastructure changes over a several-year time period or the level of investment in such changes, or both, would provide valuable information on the potentials for infrastructure to adapt to climate change risks. Public sector investments are relatively straightforward to monitor, but private sector investments are far more significant in most sectors.

Climate change impact–related capital investments have been occurring. For instance, the US Global Change Research Program (2009) reports a decision by Louisiana to elevate the highway that connects the offshore oil port with the mainland above the 500-year flood level and also to raise the level of bridges along the highway because of increased dangers of coastal flooding. The Deer Island Wastewater Treatment Plant in Boston's harbor was built 2 ft higher than mainland facilities to respond to concerns about sea level rise. In Los Angeles, eighteen recommendations for improvements to older buildings and the water and telecommunication infrastructures were incorporated in six ordinances in 2015, intended to enhance the city's resilience to threats including climate change (Jones 2015).

Much of the current information is scattered and anecdotal, but potentials exist for developing indicators of changes in the rate of infrastructure replacement, especially if federal funding assistance increases as currently proposed. Existing data sources differ by sector (for example, the Federal Energy Regulatory Commission maintains a database on filings for new construction and new capacity in the electricity industry), but investment activities and costs are generally available from private sources for all key public infrastructures.

4 Research needs

Many research needs are apparent in the descriptions of the suggested priority areas for national indicators. Here, we expand upon some and introduce several more approaches.

For each of the 16 or more different ASCE infrastructure sectors, all of the suggested indicators would require extensive research and experimentation to incorporate the four priority areas. Such efforts would depend on interactions among the public and private sectors, and expert groups (such as ASCE) with the co-benefit of more cooperation. To emphasize the importance of interactions among infrastructure users and different groups, one priority is to assess ongoing efforts to establish urban infrastructure indicators (e.g., Urban Sustainability Directors Network 2016) and to pilot a shared framework across a number of locations, with a feasibility focus, the utility or applicability, and potential for integration (Moss et al. 2019). As previously described, Koliou et al. (2020) recommend developing a "systems of systems" approach, more attention to climate hazards, and integration of different types of indicators and models to better understand damages and recovery times and pathways.

Innovative approaches for data mining web resources and other big data sources would be worth considering in consultation with expert groups, including how each of these–individually and in conjunction–might expand our capabilities in assessing the impact of climate change on infrastructure (Wang and Moriarty 2018), and what the advantages and disadvantages would be of these approaches (see, for example, Kong and Liu 2020; Wang and Moriarty 2018; Zanella et al. 2014; Ford et al. 2016; Ganguly and Steinhaeuser 2008). Specific applications to climate change and infrastructure have been advanced in the additional contexts of smart cities (Fernandes and Peek 2020). Parallel efforts such as the Resilient America Roundtable of the National Academies[1] should be tracked and incorporated as appropriate for data practices.

In many cases, sectoral impacts are relatively localized, reflecting differences from place to place in threats, vulnerabilities, and infrastructure legacies as well as interrelationships. Given the lack of comprehensive nation-wide data, one approach worth considering is the provisional use of national indicators based on monitoring a sample of local sites, emphasizing clusters of infrastructures in focal areas, as a way to begin to gather valid, comparable information on locally specific impacts and responses. The US Department of Homeland Security (DHS) is supporting analyses of this type in its sector-specific reports in connection with the National Infrastructure Protection Plan (NIPP). Meanwhile, the experiences of individual sectors at specific sites would provide information of national vulnerabilities and examples of steps in the direction of developing national infrastructure indicators.

For indicator development, the largest research challenge is on those that capture the impacts and consequences of the failure of deeply and intricately interconnected infrastructure systems. Many of these interconnections are still too poorly understood to incorporate into indicators with a high level of confidence though some of the foundations for addressing this issue are beginning to emerge as described in Section 3.3. Related to this need is research to assess infrastructure thresholds where baseline conditions are examined in combination with types and severity of climate change impacts to determine when catastrophic failures could occur. This information could inform both the development of leading indicators of when failure could occur and ways to improve the resilience of infrastructure to future events.

It would be highly beneficial to also support research to improve knowledge of sensitivities of infrastructures to climate change effects (e.g., sensitivity curves to temperature changes) as a basis for evaluating design criteria and monitoring changes in sensitivities through time. In some cases, sensitivity curves are readily available, but such sensitivity curves have not been defined for all infrastructures of interest—and especially not for infrastructure interdependencies. For example, it is possible that

[1] See https://www.nationalacademies.org/our-work/resilient-america-roundtable for more information.

US Energy Information Agency and US Environmental Protection Agency data from extreme weather events and cascading blackouts could be mined to estimate granular fragility curves. In fact, in some cases, it might be possible to estimate fragility curves at a detailed scale (e.g., county) as a function of time. In addition, the challenge of developing indicators of the social capital context within which infrastructure failures are absorbed and responses are developed deserves further study.

In summary, research needs arise to address gaps across the four priority areas identified above. Some examples of these needs presented in this section include data mining, pilot studies, expanding databases through monitoring and investigation, and adapting commonly used methods for analyzing infrastructure sensitivities to incorporate climate change. In spite of a large literature in each of these four priority areas separately, combining these priorities is challenging and is yet another research need.

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