Recommendations for Investing in Infrastructure at the Intersection of Resilience, Sustainability, and Equity

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Infrastructure systems—including water distribution, power, communications, and transportation systems—are critical to our public health and safety, national security, and economic growth. These systems, however, are aging and subject to increasing threats from both natural disasters and targeted attacks. With the significant funds that have been proposed and recently allocated to address America's infrastructure shortfalls, now is the time to think about what that infrastructure can and will look like for the future. Our goal should be investing in infrastructure that will result in resilient, sustainable, and equitable systems in support of communities. Resilient systems have "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (White House 2013). Sustainable systems are able to "meet our own needs without compromising the ability of future generations to meet their own needs" (Brundtland 1985). Equitable systems "meet the needs of underserved communities through policies and programs that reduce disparities while fostering places that are healthy and vibrant" (EPA 2021). While each of these goals is important on its own, their intersection poses opportunities and challenges in how we comprehensively think about infrastructure and its interactions with people and communities. This paper provides seven recommendations for how we should think about and invest in infrastructure to achieve resilience, sustainability, and equity goals. They represent key advances over past practice to achieve the systems we want for the future.

Transform Thinking from Reactive to Anticipatory and Forward-Looking

Historically, our investments in infrastructure have been reactive. Something breaks, and it gets fixed. A problem grows until it needs to be addressed, and infrastructure is developed to meet it. This has extended to the current state of affairs, where I have talked with too many infrastructure managers and utility operators who, operating on tight budgets, have barely enough resources to put out daily fires, much less think about more strategic preventive or anticipatory spending. The result is far from optimal. We can barely maintain what exists, and many areas require continued investment of resources without improvements in service. Typical examples are communities with perennial resource shortfalls unable to restore or fix items in disrepair or with the budget to rebuild areas that are repeatedly damaged, e.g., during annual flood or storm events.

For both infrastructure maintenance and new builds, we need to transform our thinking from reactive to anticipatory. We need to *anticipate* what future problems and needs might be and address these areas before they fail, fall short, or fail again the next time. A forward-looking rather than backward-looking approach will lead to infrastructure that is more resilient, sustainable, and equitable. It will anticipate future conditions and be designed to withstand potential disruptions (increasing resilience), it will look to utilize future resources more efficiently without compromising current service (increasing sustainability), and it will serve the needs of both current and future communities and their populations (increasing equity).

A roadmap to achieving such systems involves shifting the focus from build and repair when broken to design and mitigate before damage happens. The idea of mitigation impacts both new builds and maintenance, with mitigation applying to anticipating future needs for, demands on, and threats to infrastructure and designing new infrastructure accordingly, as well as maintaining and mitigating potential issues for existing infrastructure before they occur. Several concrete actions can be taken to achieve this. First, move (or strategically place) critical assets. If assets are continually in danger, e.g., located in a flood zone, move them out of harm's way to higher ground. Rather than allowing an asset to be flooded and fall out of service every time a storm event occurs, anticipate the next storm, and locate your critical asset at a site that is not expected to be flooded in a storm. Second, protect critical assets. In cases in which it is infeasible to move a critical asset, take protective measures to increase the likelihood that a critical asset will be protected in the next hazard event. In a seismic zone, install seismic retrofits to increase protection under future earthquake events; in flood zones, design green infrastructure to decrease flood risks to assets; and in wildfire-prone areas, clear surrounding brush and install fire protection systems.

Third, build in system redundancies that allow a system to continue operating even if part of it fails. Too many current infrastructure systems have single points of failure (Murray and Grubesic 2007), where disruption to, or failure of, a single component of the system leads to large system-wide impacts. While building system redundancies requires additional resources, if they are chosen strategically, they can increase expected system performance under a range of potential disruption scenarios.

Each of these actions and strategies will serve to increase service provision to communities under a variety of threats and scenarios, both now and into the future. Other system-specific mitigation strategies can be designed and implemented depending on given local hazards, existing and desired system designs, and community characteristics. Such an anticipatory approach to infrastructure will increase system resilience to disruptions, prolong the long-term viability and sustainability of the systems, and enhance equity by providing uninterrupted service, particularly in prioritized marginalized or underserved communities. Such an approach also looks ahead to expected threats to critical infrastructure systems and future desired outcomes from infrastructure so that we can take action in terms of design and mitigation now rather than just react and

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respond to adverse events (that we know will happen) after they occur.

Increase Planning Timelines and Revalue the Future

The foregoing recommendation raises the issue of the time-dependent nature of infrastructure. Infrastructure consists of long-lasting investments, with assets designed, built, and repaired now impacting community lives decades into the future. Traditional processes operate by fiscal year, necessarily diminishing the incentives and ability to accommodate the longer planning timelines that would benefit strategic infrastructure investments.

In planning for resilience, often the event we want a system to be resilient to is a large-scale event that happens only once every 10, 20, or 100 years. Sustainability by definition considers long-term phenomena, e.g., climate change (IPCC 2021), shifting heating and cooling demands over time (Lu et al. 2009), and long-term structural system effects (Saini and Tien 2017b). Equity impacts are often apparent years from the initial investment (Calderón and Servén 2014). Current investments to improve infrastructure performance under future scenarios will require additional upfront costs, which traditional cost-benefit analyses with discount rates applied to the long-term cost of capital will reject under long planning horizons. While recognizing the time value of money, we need to revalue the future to enable an increase in planning timelines for critical infrastructure.

For example, building system redundancies, such as adding battery backups to be able to continue to operate under a future power outage scenario, will be associated with higher upfront investment costs. However, savings will be realized when an outage occurs and the system is able to continue operating without alternate service options or potential penalties from regulatory agencies for disruptions of service. Retrofit investments operate similarly, where a retrofit action will incur an upfront cost. However, when that hazard occurs, the savings from the retrofit will be realized, in terms of both not needing to pay for extensive postevent repairs and not having system-level effects or outages due to that asset's being out of operation. The idea is to invest in the design and construction of a system now for savings and improved performance under future events. However, existing investment evaluation approaches devalue the future and future environmental and community impacts of current investments, adversely affecting resilience, sustainability, and equity objectives.

Sacrificing future benefits for maximum savings now is not the way to achieve resilient, sustainable, and equitable infrastructure. Of course, not all infrastructure investments will pay for themselves through decreased long-term costs or decreased impacts of future adverse events. However, we do need to find ways to value the future and in particular resilience-, sustainability-, and equity-based design objectives to choose and prioritize the specific actions and infrastructure investments undertaken to achieve these goals. Only then will we be able to design for resilience, sustainability, and equity objectives that will be realized years or decades in the future.

Implement Risk-Based Approaches for Infrastructure Design and Decision-Making

One of the major challenges in creating infrastructure for longer planning timelines is the *uncertainty* inherent in the problem. For resilience to hazard events, we do not know what type of storm will hit next, where it will hit, or what the impacts will be. Predicting the next earthquake is even more difficult, and while cybercrimes are increasing, where the next cyberattack will occur and how extensive it will be are unknown. Sustainability objectives are subject to uncertainty, with the natural environment behaving in unpredictable ways, exhibiting cascading and compounding effects on structures and infrastructure and on the environments in which they operate. In designing for equity, people—notoriously unpredictable—are key. What people want and how communities will change and develop over time are unknown. We can make projections, but people often surprise us.

Thus, within this environment, it is critical to be able to assess, plan, and design infrastructure that accounts for these multiple sources of uncertainty. While risk-based approaches have been part of the research literature in infrastructure planning for many years, enabling us to look beyond single scenarios to formulate design guidelines that ensure a level of service across a range of possible future outcomes (Tsang et al. 2002; Lienert et al. 2015; Applegate and Tien 2019), these approaches have been slow to translate into practice, especially in areas outside of seismic design. We need to upend traditional deterministic infrastructure planning and design for single future scenarios and opt for probabilistic risk-based design to quantitatively and rigorously include uncertainty in the analysis.

In addition, we need to move from designing for the mean to designing for *extreme events*. Traditional structural and infrastructure design has been based on averages, i.e., the most likely scenario, and adding a safety factor on top of that. As we see events that are increasingly extreme compared to the historical record, it is no longer acceptable to treat extreme events as rare events for which a system may or may not be designed to withstand. Risk-based approaches are particularly well-suited for this type of analysis, with methods that enable analysis of extreme rather than just mean system responses, e.g., maximum structural responses under a given event (O'Rourke et al. 2016; Saini and Tien 2017a; Zhang et al. 2019). Extreme event responses are often those that result in the most damage and impacts to communities. We have the ability to make informed predictions on what these extremes will look like in the future. There are certainly limitations in making such forecasts, particularly when they are based on historical data that may not hold in an increasingly dynamic world, and there is further uncertainty in how environmental and technological factors will evolve in the future. However, at this point, it is irresponsible to not explicitly design for extreme events, many of which we know now will occur with increasing frequency and severity going forward. The recommendation here is to implement risk-based approaches to be able to confidently make decisions regarding infrastructure investments under conditions of uncertainty while designing for the extremes.

Evaluate Benefits of Infrastructure by Community Impacts

This recommendation focuses on changing how we measure infrastructure performance. We need to change our thinking and evaluation of infrastructure from system downtimes and outage hours to actual impacts on people. The purpose of infrastructure is to serve communities. Thus, we need to measure infrastructure outcomes based on their *community impacts*. One concrete measurement of this type is to measure the changes in population impacts for a given infrastructure investment (Lee and Tien 2019). Then we can make comparisons across potential infrastructure investment strategies to prioritize and select those that will have the largest impact with the greatest return on initial investments. For example, if two potential investments result in differing reductions in impacts under a potential outage scenario, e.g., increased protection by number of people, housing units, and critical facilities affected, and the initial investment levels for the two options are comparable, choose the option leading to the greatest expected benefit to the community. Resilience in particular encompasses infrastructure, hazard-specific, and social aspects (Johansen et al. 2017). Tying infrastructure systems to direct population impacts is a way to quantitatively evaluate and select among infrastructure investment options.

Other sustainability and equity measures can be similarly explored. For sustainability, resource use by infrastructure can be considered in evaluating current and future benefits of infrastructure. For equity, we know that disruptions in infrastructure services can disproportionately affect vulnerable populations (Chang 2016). To increase equity in infrastructure investments, additional socioeconomic variables must be taken into account in assessing population impacts. By including this myriad of variables in evaluating infrastructure benefits, we can begin to examine the tradeoffs between resilience, sustainability, and equity objectives in infrastructure investments and select those options that achieve multiple benefits among the suite of possible infrastructure investment options.

Work across Silos to Consider Infrastructure as Interdependent Networks

As we begin to think about potential tradeoffs between resilience, sustainability, and equity objectives, we see that infrastructure is by nature complex. In addition to having multiple intersecting objectives, its system components exhibit multiple interactions, and its operations are embedded within complex governance and community structures. We need to expand how we think about infrastructure to embrace these complexities and the interdependencies that exist between infrastructure, its multiple objectives, its mode of operation, the institutions that govern it, and the people it serves.

Traditionally, infrastructure has been treated as individual, independent systems. Water system managers oversee water treatment plants and water distribution systems. Power utilities manage and operate power grids. Such an approach is no longer sufficient when it comes to describing the complex infrastructure ecosystem that now exists (Tien 2018; Sattar et al. 2021). Instead, infrastructure must be treated as interdependent networks, in which multiple systems depend on each other to function.

I once worked with the city of Atlanta to assess the importance of including interdependencies in infrastructure analyses and understanding how ignoring interdependencies will lead to underestimations of system vulnerabilities (Applegate and Tien 2019). The project highlighted interdependencies of not just physical systems but also of organizations and people. The project required working across traditional silos, implementing information sharing across entities and organizations and shifting the thinking about infrastructure from operating in isolation to operating within a larger interdependent network.

Just as infrastructure systems do not function in isolation, infrastructure investments cannot be effectively made in isolation or by single agencies or organizations. We need institutions and governance structures that encourage *cross-sector activities*, such as joint infrastructure evaluation boards that break down traditional functional silos. Everyone with a stake in the outcome needs to be at the decision-making table since representative governance and responsible and responsive management will be critical to successful infrastructure investments and operations that promote resilience, sustainability, and equity. For resilience, we need a more comprehensive view of infrastructure networks—and the ability to make decisions across these networks—to protect against *cascading effects*, in which a single failure or outage leads to more widespread outages across multiple systems and communities (Guidotti and Gardoni 2018; Johansen and Tien 2018; Cardoni et al. 2020). A siloed approach neglects these critical failure mechanisms. For sustainability, we know that environmental impacts are not contained within human-drawn boundaries, and natural and built systems need to be thought of together and holistically to capture effects relevant to wide-ranging phenomena such as climate change. For equity, we need representative governance in infrastructure spending and management to protect against decisions that serve only narrow self-interests. Because infrastructure is viewed more comprehensively, such diverse and cross-functional governance structures will increase the likelihood for advances in infrastructure investments across multiple resilience, sustainability, and equity objectives for increased community and population benefits.

Expand Risk Profile beyond Physical Infrastructure Risks to Include Cybersecurity Risks

As we look toward the future of infrastructure, a critical element that has been largely neglected in traditional infrastructure engineering is the design for and mitigation of cybersecurity threats. Risk assessment of critical infrastructure has methods to account for physical risks. However, infrastructure is becoming increasingly reliant on telecommunications and cybersystems for monitoring, automation, and control functions, e.g., instrumentation for remote monitoring and automated responses to detected faults such as redirection of load across a power grid or adjustment of chemical levels in a water treatment plant. Such advances have led to increases in efficiency and improvements in system performance; however, they also leave critical infrastructure increasingly vulnerable to *cyberattacks*.

We need to expand the risk profile considered for critical infrastructure, beyond traditional physical infrastructure risks such as breakage, leakage, and outage scenarios, to include cybersecurity risks and the potential for targeted attacks. Such cyberthreats differ from natural hazards in that their targeted nature means that particularly vulnerable elements of a network can be impacted to achieve maximum system-level damage. The likely impacts of such an attack make cybersecurity risks even more critical to consider. Potential targets range from local municipalities to regional and national levels, with US infrastructure a growing target of cybercrime and cyberterrorism (Albahar 2019). In addition, the emerging *transition to 5G* will introduce, along with its new capabilities, many new risks to both the telecommunications system itself and the critical infrastructure systems and functions relying on 5G to operate. In the development of smart transportation systems, for example, the cybersecurity risks associated with the dependence of connected and automated vehicles on 5G will have significant impacts on network safety and performance (Vargas and Tien 2022), particularly if left unchecked with risks unmitigated. These risks will only multiply as the range of smart infrastructure systems continues to develop. In this rapidly changing environment, and with the anticipatory approach we must now take to infrastructure planning and design, we have the opportunity to address these risks now before full systems are deployed and before the anticipated disruptions occur.

Increase Availability and Use of Data for Infrastructure Monitoring, Analytics, and Control

Finally, we live in an increasingly data-rich world. Traditional infrastructure systems, however, have been slower than many

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industries to adopt and utilize data science approaches to improve system performance. Sensing technologies are expanding in capabilities and performance, with the use of data analytics on monitoring data providing the opportunity for *real-time detection* of anomalies or predictions of system performance (Ghernaout et al. 2018; Saini and Tien 2018). For infrastructure that is aging and that cannot be replaced under currently existing budgets and available resources, sensors and their associated data measurements provide a way to *monitor the safety* of a given structure or infrastructure asset (Seo et al. 2016; Sony et al. 2019). In aging bridges, for example, data on corrosion and scour levels can be included in the risk assessment of bridge assets across a transportation network (Zhang et al. 2019; Zhang and Tien 2020). As the number and types of data on infrastructure increase (Tien et al. 2016), we need to provide avenues and opportunities for cross-organizational data sharing to combine these data sources in strategic ways to better understand a given infrastructure system and its performance. *Integrating information* from data collected across sources provides increased accuracy, benefits, and understanding of real-time situations, in comparison with single sources of data alone (Lee and Tien 2018).

Increasing the availability and use of data for infrastructure operations carries multiple benefits, particularly with respect to supporting our goals of increasing the resilience, sustainability, and equity of these systems. Data can lead to increased resilience by decreasing the time needed to detect anomalies and increasing the speed of response to minimize the negative impacts of system disruptions, increased sustainability by providing continuous monitoring information on the environmental impacts of infrastructure operations, and increased equity by providing valuable information about infrastructure services rendered across populations and communities over time. We must also be cognizant, however, of the potential vulnerabilities of such increased data and use in the increasingly cyber world in which we will operate, including possibilities of data alteration and spoofing to artificially manipulate infrastructure systems for malicious purposes. The future applications of using data to inform infrastructure monitoring and control are expanding; it will be in our best interest to harness such capabilities—while mitigating potential risks of these new capabilities—as we look toward the future of infrastructure.

In summary, the recommendations described here provide key signposts for planning, designing, and investing in infrastructure that will increase the resilience, sustainability, and equity of the communities these systems serve. The problem of America's infrastructure is complex. We have the opportunity now to change how we approach these systems: shifting from reacting to adverse events to anticipating future needs; valuing the future in increasing infrastructure planning timelines; implementing risk-based approaches that explicitly design for extreme event scenarios; evaluating infrastructure benefits by people-focused community impacts; working across physical, organizational, and governance silos to treat infrastructure as interdependent networks; including cybersecurity risks in infrastructure risk mitigation strategies; and increasing the use of data in infrastructure operations. All of these actions will work together as critical pathways to investments in infrastructure that will increase the resilience, sustainability, and equity of our communities for the future. Now is the time to act.

Data Availability Statement

Data used during the study are available from the author upon reasonable request.

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