Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure

As climate change impacts emerge ever more forcefully around the globe, decision makers have begun to ask, with increasing urgency, how they can make their communities and businesses more resilient. One obvious place to start is infrastructure—those structures and systems, such as roads, bridges, and water treatment facilities, that are designed to last fifty years or more. If communities can make their investments in infrastructure resilient to the impacts of climate change, they can increase the likelihood of rapid recovery from extreme events and better protect economic strength, public health, and security. Infrastructure is the backbone to building resilience. Making sure it can withstand not only the next storm but also future climate-exacerbated storms is a goal that all should embrace. But how do cities and regions build or retrofit infrastructure so that is resilient to climate change? It is this question that this paper seeks to begin to answer.

This effort was borne out of discussions between the authors of this essay and reflects our shared observation that the basic question of how to build climate-resilient infrastructure is just beginning to be answered across the relevant sectors of finance, engineering, and planning. In an effort to better understand the challenges and identify the most promising opportunities, the Hoover Institution, along with non-financial sponsors the American Society of Civil Engineers Committee on Adaptation to a Changing Climate, Stanford Urban Resilience Initiative, and the University of Maryland Center for Technology and Systems Management, co-convened a series of meetings with individuals and institutions who are helping to lead global efforts to make infrastructure more resilient. To gain better insight, we drew from a broad range of perspectives—from engineering to planning, from developing to developed countries, and from risk mitigation to disaster response. The ideas captured here reflect that breadth and the thoughtful input of representatives from thirty-three organizations, including policy makers, emergency managers, financiers, development experts, and climate scientists, together bringing decades of experience to bear.

We need to accelerate the pace at which we identify and address climate risks. We need to learn faster and broadly apply the best ideas that are not yet in widespread practice. This publication offers a road map on how to accomplish these goals, identifying principles, strategies, and steps to scale up resilience. Our collective hope is that it can help guide the important journey of ensuring the resilience of critical infrastructure to future climate impacts. We encourage an ongoing dialogue to quicken global learning.

How Can We Design, Fund, and Build Resilience into Public Investments in Infrastructure?[1]

We are in a race against time to improve the resilience of the world's infrastructure. With each passing year, our infrastructure is increasingly stressed as we try to meet the needs of a growing population and withstand the impacts of a changing climate. Although governments and the private sector invest billions of dollars in new infrastructure each year, that infrastructure is not routinely designed for the increasing effects of storms, floods, droughts, wildfires, and other hazards that climate change brings, and thus the world's investments in infrastructure themselves are not yet resilient to the impacts of climate change. Failing to ensure the climate resilience of infrastructure will have major economic consequences. We can and must do better. The broad principles, strategies, and steps described in this paper are intended to help the world achieve climate-resilient infrastructure.

The Demand for Infrastructure and the Need for Resilience

Demand for infrastructure investment is increasing worldwide. From 2015 to 2030, $90 trillion in new infrastructure investments will be needed—an amount equivalent to the world's total existing stock.[2] The need is particularly urgent in rapidly growing cities in developing countries.[3] Much of the world's new infrastructure will be built in these countries, which face the dual challenges of responding to natural hazards and rapid urbanization even as they work to address widespread poverty and build thriving economies. Africa, Latin America, and the Caribbean must double their current annual investments in infrastructure to achieve development objectives, while Asia will require an investment of $1.7 trillion per year in infrastructure through 2030 to maintain its growth momentum, tackle poverty, and respond to climate change.[4] The pressing demand for infrastructure—and the financing required to realize it—is an enormous challenge. It also provides an enormous opportunity to build a more resilient future.

Without significant improvements in infrastructure resilience, annual economic losses from natural disasters' damage to urban infrastructure alone will increase from $250 to $300 billion currently to $415 billion by 2030.[5] Damage from Hurricanes Harvey, Maria, and Irma, for example, made 2017 the most expensive hurricane season in US history, with approximately $265 billion in damages from those three storms alone.[6] With accelerating impacts from climate change—including sea-level rise, more extreme heat events, bigger storms, increasing precipitation, and deeper droughts—these losses will continue to grow.

Developing more resilient infrastructure involves a broad range of actors. They include policy makers, planners, investors and the financial sector, industry representatives, designers, engineers, researchers, disaster response professionals, standards developers, beneficiaries, and community members. Together they are shaping the physical structures and services required to meet communities' needs for decades to come. All are stakeholders in the long-term viability of infrastructure. Awareness is growing among these stakeholders of the need to address these challenges. Yet the best existing ideas to achieve resilient infrastructure are not yet in widespread practice.

We need to move faster. We need to scale up good practices rapidly even as we advance our understanding of infrastructure resilience. Quicker action today can help ensure that current investments are sound and will contribute to a more resilient future. Below we outline several broad principles, strategies, and concrete steps needed to address this challenge at a wider scale.

Principles

Several high-level principles should guide the development of more resilient infrastructure. The first is to ***be proactive***, doing what we can now with both existing knowledge and foresight. Uncertainty should not preclude action. A second principle is that we must ***be fair***, considering the implications of decisions for those who are particularly vulnerable. We need to directly and consistently engage affected communities in decision making. A third, related principle is to ***be inclusive***, engaging all stakeholders early and often throughout the entire process. They should include knowledge generators, knowledge users, and impacted communities. An inclusive process helps to ensure that decisions are grounded in the best available information and fit the needs and values of those affected. Inclusivity can also reduce future conflict, avoid negative unintended consequences, identify a strong pool of options, and increase support for the measures chosen.[7] A fourth principle is to ***be comprehensive***, considering the full range of risks and means to address them through planning, financing, and engineering. A holistic approach includes integrating social and ecological resilience into decisions where appropriate. Strong social dynamics and healthy, functioning ecosystems are critical to adaptive capacity—increasing

Seven Strategies for Climate-Resilient Infrastructure
1. Make better decisions in the face of uncertainty.
2. View infrastructure systemically.
3. Take an iterative, multi-hazard approach.
4. Improve and inform cost-benefit analysis (CBA).
5. Mainstream nature-based infrastructure.
6. Jump-start resilience with immediate actions.
7. Plan now to build back better.

communities' and regions' ability to respond effectively to both chronic stresses and extreme events.[8] These overarching principles provide context for implementing the strategies below.

Seven Strategies

The following strategies are distilled from the work of thought leaders across many sectors and disciplines. They are key concepts that should drive the design, funding, and building of climate-resilient infrastructure, and they apply to both individual projects and systems. They may involve changes in policies, advances in science and technology, and new practices by decision makers, including policy makers, practitioners, and investors. These strategies, if broadly applied, can produce robust and sustainable infrastructure, more cost-effective investments, and reliable services to our growing cities and populations.

1. Make better decisions in the face of uncertainty.

Engineers typically design infrastructure to withstand a certain degree of climate risk, based on the assumption that past climate is a reliable predictor of future conditions. This assumption no longer holds. Long-lived infrastructure designed using past climate patterns is at risk of underperforming or failing in the future. Climate projections carry uncertainty, as it is impossible to precisely predict the factors driving future greenhouse gas emissions and their effects on the climate. This type of uncertainty is new and distinct from risks that engineers routinely consider.[9] It creates challenges for infrastructure planners and engineers unaccustomed to managing such ambiguities. There is a risk of over- or underbuilding, which can, in turn, transfer risks to infrastructure investors or users.

Yet uncertainty about future climate conditions should not block action. Infrastructure planners should employ new approaches that facilitate adaptive decision making and design in the face of uncertainty.[10] These approaches can incorporate uncertainty into project design rather than attempting to engineer to a single climate future.[11] They also can inform decisions about how much to invest now versus later.

Working under uncertainty can require embracing flexibility to a higher degree than in the past. Building in flexibility allows us to change course. Designers can preserve options that may not seem justified or affordable today but could be important later as conditions change or new information becomes available. Future options may include more aggressive and capital-intensive measures, or designers may discard measures that no longer will be effective under future conditions. These approaches recognize the informational and budgetary constraints of today while preserving options for the future.

A corollary benefit is that decision-making methods that allow for greater flexibility can lead to consideration of a broader range of stakeholder considerations. These may include different ways of defining a failure, valuing nonmarket goods such as biodiversity, or defining the probabilities of different scenarios.[12] Managing uncertainty builds on a dialogue among decision makers, infrastructure designers, and users about the tradeoffs between siting and design options and timing, costs, and resilience. The bottom line is that explicitly accounting for uncertainty in project design can lead to better decisions.

2. View infrastructure systemically.

Infrastructure is more than individual structures. It is embedded in a complex and interconnected world and includes natural, built, and human systems. There are often strong interdependencies both within and among infrastructure systems. The failure of one infrastructure component can trigger simultaneous failures or a cascading collapse of other critical services. For example, when power supply is interrupted, services that are dependent on electricity may also fail. These may include potable water supplies, communication, and other critical infrastructure services. These failures may, in turn, affect emergency response, health care, and habitability of residential areas, ultimately disrupting the well-being and safety of communities and impacting industries and businesses.

Given the potential for these systemic impacts, it is important to screen for risks at a systems level rather than looking only at individual assets. This approach can identify interdependencies and possible interactions early in the planning process. It also can reduce the need for asset-level fixes that may be more capital intensive and less effective in achieving system-wide resilience. Systems thinking provides more opportunities to achieve broad benefits and avoid maladaptation.[13] Unfortunately, the structure of most financing and regulatory policies typically reinforces a piecemeal, project-by-project approach to risk assessment and management. Policy makers instead should work to support and incentivize holistic approaches to risk management.

Pushing risk screening upstream to the earliest stages of systems planning or project development gives planners and designers a fuller understanding of risks and a greater range of management options.[14] One of the most important stages is land use planning and zoning. Considering where to build as well as how to build can reduce risks to individual assets. Even more important, such consideration can reduce network disruptions and threats to an entire area. Steering development away from high-hazard areas will lower the costs of rebuilding after a disaster.

Looking at infrastructure as part of a system also provides more opportunities for policy makers to support effective, climate-resilient development. Decisions regarding zoning and incentives for resilient infrastructure can shape future growth, promote sustainability, and avoid costly and maladaptive construction. Maintaining consistent standards across projects also levels the playing field for developers and financiers.

3. Take an iterative, multi-hazard approach.

Infrastructure often fails as a result of a combination of natural events and breakdowns in social, technological, or institutional systems. However, conventional sensitivity analyses and risk-management approaches typically consider only one stressor or risk at a time. Since stressors rarely occur alone or lead to single impacts, a multi-hazard approach can allow designers to consider interactions among risks and domino effects that may follow.[15] Extending analysis beyond design events based on historical data is essential to improve risk management.[16] By understanding the conditions that support good performance and asking which combination of factors could break the system or cause it to fail, infrastructure designers can think more comprehensively about the value a project provides and factors that could impede that service. Designers should move beyond standard risk screening to imagine and define failure in physical, social, and economic terms and conduct a holistic multi-hazard assessment.[17] Incorporating flexibility and the other decision-making approaches described in strategy number one can help, as can planning scenarios that reveal which plans may succeed or fail. In addition, reviewing past failures caused by a combination of stressors can help identify areas of future risk. A multi-hazard approach is more realistic than conventional sensitivity analyses that examine one stressor at a time.

4. Improve and inform cost-benefit analysis (CBA).

CBA plays an important role in shaping infrastructure choices. Yet as it is traditionally practiced, CBA can lead to less-resilient choices. This occurs when CBA accounts for the upfront capital costs of infrastructure (which are higher for some resilience investments) but not the associated benefits, such as reduced operational and maintenance costs over the service life of the infrastructure.[18] The economic or financial benefits of resilience, as well as the costs of poor resilience, can be difficult to quantify. However, even when quantification is possible, the way in which a CBA is conducted can limit its ability to assess the incremental benefits of investments, cobenefits, and perverse impacts over the service life of the infrastructure.[19] In addition, CBA does not explicitly account for the value of strategies that preserve future options, even though a flexible, adaptive management approach to resilience may yield benefits as socioeconomic and environmental conditions change over time.[20] Traditional CBA also may include a range of other limitations.[21] These include difficulty in addressing uncertainty and failure to value nonmarket goods and services. Undervaluing the benefits of ecosystem services can lead to a preference for “gray” (conventional) or built infrastructure instead of green infrastructure (see strategy number five).

Because many investors require use of CBA, it is important to improve and inform its use. There are approaches to project evaluation that address some of the concerns listed above.[22] To better assess a project, CBA should consider the full life-cycle costs, the benefits of investing in resilience, and the costs of inaction and unintended consequences.[23] Given these complexities, project analyses should recognize the limitations of CBA. Representing the value of a project in a single number may not provide the full picture, and decision makers may benefit from additional quantitative and qualitative information not typically accounted for in traditional CBA.

Extending a revised approach to CBA to the financial analysis of infrastructure investments can improve risk assessments and identify resilience measures that lower financial risks. Treating climate risks as an integral part of the overall financial analysis of infrastructure investments has the potential to enhance not only the physical resilience of infrastructure but also the financial resilience of the investment. Infrastructure funders routinely assess risk factors that include overall commercial viability, completion risks, environmental risks, operating risks, revenue risks, input supply risks, and contracting risks.[24] Climate change can impact each of these factors, and such impacts can be measured in terms of the overall financial value at risk. Financial institutions should incorporate climate risk into the cost of financing and reduce financial incentives to projects that are riskier by design. Financiers can promote resilience through the financing of resilience measures, better risk sharing among financial investors for public and private infrastructure projects, and a comprehensive approach to procuring insurance or other risk-transfer mechanisms.

5. Mainstream nature-based infrastructure.

The use of nature-based, or green, solutions as either alternatives or complements to conventional, or gray, infrastructure can help reduce risks, enhance resilience, and support other objectives, including ecosystem restoration, protection or creation of green space and recreation areas, and climate change mitigation through carbon sequestration.[25] On its own, green infrastructure may be able to reduce risks from some hazards.[26] For example, mangroves protect coasts from wave damage and erosion, in addition to providing cobenefits such as breeding grounds for fish and carbon sequestration.[27]

A combination of nature-based and conventional infrastructure may increase overall resilience. This combined approach can provide redundancy and improve resilience to unexpected events that coincide or cascade. For example, during a severe storm, healthy wetlands can reduce the impacts of storm surge on coastal communities, reduce strain on constructed storm drainage systems, and mitigate the risk of flooding and damage to infrastructure. At the same time, these solutions may respond differently to a range of hazards, thereby increasing system robustness through complementary adaptation responses.

Investors may be hesitant to invest in nature-based infrastructure without a clear understanding of its costs, benefits, and performance relative to conventionally built infrastructure. Often nature-based solutions are excluded from traditional analyses such as CBA, even though they may be effective in managing certain risks.[28] In some cases, they can achieve comparable resilience at lower cost, provide cobenefits that are typically not accounted for, or provide a flexible strategy that can be readily scaled up or adapted to respond to changing conditions.[29] Both nature-based and conventional approaches have benefits and costs. To most effectively manage risks, it is important to consider a full range of options, and how they may reinforce one another.

6. Jump-start resilience with immediate actions.

Uncertainty about the specifics of climate change and its local impacts should not delay action. Infrastructure projects can get mired down in assessments of vulnerability and uncertainty, and analysis paralysis can deter efforts to increase infrastructure resilience, reinforcing the perception that resilience measures are time consuming, costly, and complicated. Yet some measures have low or no incremental cost and little potential for later regret. This is especially true of measures that can be integrated at the beginning of new infrastructure projects or in the course of regular maintenance cycles for existing infrastructure. Analysis to support these measures can be relatively quick, and existing resources may allow for immediate implementation.[30] Easily adopted resilience measures include using pavement mixtures adapted to different extreme temperatures and freeze-thaw cycles; increasing culvert size to accommodate higher peak-flood levels; adjusting concrete composition to withstand ocean acidification; changing maintenance protocols to remove debris from drainage systems that may clog during severe rain events; and removing vegetation that may threaten power lines during wildfires.

While these rapidly deployable measures are not a substitute for longer-term solutions, they can be useful starting points to reduce risk and demonstrate results. Quick, effective actions can generate support for transformational measures that are more complex, capital intensive, and time consuming.

7. Plan now to build back better.

Building back better can save money. Globally, the World Bank estimates that $173 billion in annual disaster losses could be avoided if rebuilding were to be improved after each disaster over the next twenty years.[31] However, there are myriad social, financial, and institutional constraints to improved rebuilding in the wake of devastating storms and other weather-related disasters. Communities need to get back on their feet quickly, yet swiftly rebuilding and replacing what was there too often re-creates or increases vulnerability to future climate change impacts.[32] People's understandable desire to get back to normal as quickly as possible can be stymied by insurance-related delays, zoning and property rights disputes, and restrictions on how recovery funds can be spent or matched.

Postdisaster periods can provide unique windows of opportunity to promote resilience. Significant funding is most likely to be available at these times; public interest and political will often are at their highest; and major steps to foster climate-resilient development may seem more feasible. To make use of this opportunity, planning should occur well in advance of disasters so that strategies will already have been negotiated with stakeholders and will be ready for quick deployment. Predisaster planning can be valuable even when the anticipated disaster does not occur, as it charts a path toward greater resilience. Policy makers and other infrastructure actors should support communities in creating visions for a resilient future that can be pursued incrementally, while also building blueprints for broader transformation should a disaster occur. The latter may involve moving people, assets, and infrastructure out of harm's way rather than rebuilding in high-risk areas. Making carefully considered, risk-informed investments in the wake of disasters can build more resilient communities and protect people, property, and taxpayer dollars from future loss and disruption.[33]

Getting to Scale

Climate change has put us in a race against time: we need to ensure that the billions of dollars invested in infrastructure each year are well spent. Infrastructure investments must fulfill their objectives over their entire design life, but today, unfortunately, much of the planning and work needed to make infrastructure resilient is custom tailored to each situation. We urgently need to move from individual case studies to broadly applicable approaches. We need to achieve resilience at scale. A number of actions, outlined below, can scale up the development of climate-resilient infrastructure.

First, invest in building human capacity and knowledge among all stakeholders.

We need to learn faster: adapting infrastructure requires new skills and abilities in diverse fields. More people need the capacity to make and implement better infrastructure decisions in the face of uncertainty, including policy makers, planners, investors and the financial sector, industry representatives, designers, engineers, researchers, disaster response professionals, standards developers, and community members. Building capacity is particularly challenging where access to financial resources or cutting-edge expertise is limited. Developed countries have remote and economically disadvantaged areas. Developing countries, where most of the world's new infrastructure will need to be built, face the greatest challenges.

We need more effective strategies to build capacity throughout our educational processes. ***Formal education***—which creates the essential foundation for resilience work across all disciplines—requires developing appropriate curricula and modules for training professionals at different levels of sophistication. ***Learning by doing*** is important as well, given the need to move forward now while developing better approaches for the future. It is also important to ***learn from others*** to avoid needlessly duplicating efforts and to accelerate learning. ***Advancing research*** that underpins decision making is critical. Work is now under way—by the US Global Change Research Program, the National Academies of Sciences, Engineering and Medicine, and other bodies—to provide better information for decision making. Similarly, programs such as the Least Developed Countries Universities

Consortium on Climate Change are building international capacity through training and research. These and other ongoing efforts are useful; more of them are needed to get to scale.

Second, develop and update standards and manuals of practice for climate-resilient infrastructure.

Most building codes and design standards do not account for a changing climate. The development and revision of standards is typically a slow process. Informational materials created by some professional associations can be useful in demonstrating how and why considering climate change is important in building codes, standards, and manuals of design, engineering, and planning practice.[34] While much climate science has advanced sufficiently to inform decision making, a central challenge remains: bringing these advances into engineering practice in the form of technical basis documents. ***Transitioning science to the engineering practice*** requires the collaboration of practitioners and scientists in research and development. Together they can best craft the kinds of workable solutions that underlie new or revised standards. In addition, ***investment and appraisal methods*** are needed to incentivize financing for the least-cost pathway forward.[35] Underlying all of this would be ***financial and technical support from agencies***, such as the National Science Foundation, the Department of Energy, and the National Institute of Standards and Technology. This support is important for the development of technical basis documents that are a foundation for standards. Preparing manuals of practice and professional guides can serve as steps toward the development of standards, while also providing interim opportunities for advancing engineering practices.[36]

Finally, get the incentives right.

Doing so requires ***incentivizing the financing of climate-resilient infrastructure***. The gap between current expenditures and investment needs is massive. Achieving climate-resilient infrastructure at the scale necessary to narrow this gap will require mobilization of both public and private finance. Some governments are using their purchasing to increase the resilience of their investments. For example, New York City and the US Federal Emergency Management Agency are using government-funded infrastructure investments to promote "beyond code" compliance, meaning that they are raising standards above the minimum requirements of local building codes.[37] Often, however, federal, state, and local governments inadvertently do just the opposite, encouraging risky behaviors, such as rebuilding in flood zones after a disaster. There is a need, particularly in the short term, to incentivize investments (through, e.g., resilience tax credits, loans, grants, etc.) to accelerate investments in resilience.

At a global scale, development banks are ***mainstreaming climate resilience into investments*** by performing individual risk assessments for a country, sector, and/or individual investment. For example, the World Bank is developing a rating system to promote public- and private-sector investments in adaptation.[38] The Global Commission on Adaptation seeks to incorporate climate change risks into planning and is engaging financial institutions, national finance ministries, banks, and businesses to increase resilient investments. Going forward, a linchpin of success will be ***engagement of the private sector***, which is responsible for constructing and managing a significant fraction of the world's infrastructure. The financial and business case for resilience should integrate climate risk assessments into investment decision making and monetize the potential financial return from resilience investments. This practice should be paired with identifying appropriate financing pathways, including public-private partnerships, so that the full potential of private-sector engagement can be realized.

A range of ***new policies*** can create powerful incentives for resilient infrastructure. Smart land-use planning and zoning can promote resilient growth. Building standards can create a floor for performance and resilience. It is beyond the scope of this paper to fully explore the range of relevant policies, but most actions described above have a policy component.

Moving Forward

Globally, we have gained experience in how to develop and maintain more resilient infrastructure. Now is the time to move forward, accelerate learning, and scale up. The ideas outlined here can help us to ensure that the trillions of dollars in infrastructure investments contribute to a more resilient future. We encourage an ongoing dialogue to accelerate the pace at which we learn from one another. Together we can plan, build, and maintain infrastructure resilient to our changing world.

NOTES

1 For the purposes of this discussion, *public investments* means federal, state, and local investments funded through taxpayer financing or borrowing and includes funds for international development.

2 Inter-American Development Bank (IADB), "Inter-American Development Bank Sustainability Report 2017" (2017), http://dx.doi.org/10.18235/0001034.

3 US Agency for International Development (USAID), "Climate Resilient Infrastructure Services: Lessons Learned," prepared by Engility Corporation and ICF International (2015a), https://docs.google.com/a/ccrdproject.com/viewer?a=v&pid=sites&srcid=Y2NyZHByb2plY3QuY29tfGNjcmR8Z3g6NGFiMGI3MDFlM2ZjNjM4MA.

4 For Africa, see ibid.; Infrastructure Consortium for Africa (ICA), *Infrastructure Financing Trends in Africa—2016* (Abidjan, Côte d'Ivoire: 2017), https://www.icafrica.org/fileadmin/documents/IFT_2016/Infrastructure_Financing_Trends_2016.pdf; and African Development Bank (AfDB), *African Economic Outlook 2018* (2018), https://www.icafrica.org/fileadmin/documents/Knowledge/GENERAL_INFRA/AfricanEconomicOutlook2018.pdf. For Asia, see Asian Development Bank (ADB), *Meeting Asia's Infrastructure Needs* (2017), https://www.adb.org/publications/asia-infrastructure-needs.

5 United Nations Development Programme (UNDP), "Disaster Recovery: Challenges and Lessons" (2016), http://www.undp.org/content/dam/undp/library/Climate%20and%20Disaster%20Resilience/UNDP_Recovery%20Infographic_Final_16April2016.pdf.

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7 US Department of Energy (US DOE), *Climate Change and the Electricity Sector: Guide for Assessing Vulnerabilities and Developing Resilience Solutions to Sea Level Rise* (2016), https://www.energy.gov/sites/prod/files/2016/07/f33/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Assessing%20Vulnerabilities%20and%20Developing%20Resilience%20Solutions%20to%20Sea%20Level%20Rise%20July%202016.pdf; US DOE, *Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning* (2016), https://www.energy.gov/sites/prod/files/2016/10/f33/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Climate%20Change%20Resilience%20Planning%20September%202016_0.pdf; "Collaborative Risk Informed Decision Analysis (CRIDA)" (2017), http://test1.agwaguide.org/CRIDA; National Institute of Standards and Technology (NIST), "Community Resilience Planning Guide" (2015), https://www.nist.gov/topics/community-resilience/community-resilience-planning-guide; and Graham George Watkins, Sven-Uwe Mueller, Hendrik Meller, Maria Cecilia Ramirez, Tomás Serebrisky, and Andreas Georgoulias, *Lessons from Four Decades of Infrastructure Project-Related Conflicts in Latin America and the Caribbean* (Inter-American Development Bank [IADB]: 2017), http://dx.doi.org/10.18235/0000803. Zamuda, C., D.E. Bilello, G. Conzelmann, E. Mecray, A. Satsangi, V. Tidwell, and B.J. Walker, 2018: Energy Supply, Delivery, and Demand. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 174–201. doi: 10.7930/NCA4.2018.CH4

8 Karin de Bruijn, Joost Buurman, Marjolein Mens, Ruben Dahm, and Frans Klijn, "Resilience in Practice: Five Principles to Enable Societies to Cope with Extreme Weather Events," *Environmental Science & Policy* 70 (2017): 21–30, https://doi.org/10.1016/j.envsci.2017.02.001.

9 Some experts refer to this as "deep uncertainty," which emerges when future conditions cannot be reliably quantified, either because the mechanisms involved are too complex to be modeled or because the parameters of the model may vary over time. See Laura Tuck and Julie Rozenberg, "Embracing Uncertainty for Better Decision-Making," *World Bank Group Infrastructure & Public Private Partnerships Blog* (2016), http://blogs.worldbank.org/ppps/embracing-uncertainty-better-decision-making.

10 American Society of Civil Engineers (ASCE), *Climate-Resilient Infrastructure: Adaptive Design and Risk Management*, edited by Bilal M. Ayyub (Committee on Adaptation to a Changing Climate: 2018), https://ascelibrary.org/doi/book/10.1061/9780784415191; Bilal M. Ayyub and George J. Klir, *Uncertainty Modeling and Analysis in Engineering and the Sciences* (Chapman & Hall/CRC Press: 2006); and Climate-Safe Infrastructure Working Group (CSIWG), *Paying It Forward: The Path toward Climate-Safe Infrastructure in California* (Sacramento, CA: 2018), http://resources.ca.gov/climate/climate-safe-infrastructure-working-group. Examples of new design approaches that address uncertainty include robust decision making (RDM), probabilistic risk management, real options analysis (ROA), Climate Risk Informed Decision Analysis (Mendoza et al. 2018), and adaptation pathways.

11 World Bank, *Hydropower Sector Climate Resilience Guidelines* (2017), beta version.

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16 De Bruijn et al., "Resilience in Practice."

17 UCS, "Principles for Climate-Smart Infrastructure."

18 Deloitte Access Economics, *Building Resilient Infrastructure* (Sydney, Australia: 2016), https://www.iag.com.au/sites/default/files/Documents/Announcements/ABR_Report-Building-resilient-infrastructure-020316.pdf.

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20 R. de Neufville and S. Scholtes, *Flexibility in Engineering Design* (Cambridge, MA: MIT Press, 2011).

21 Additional challenges to CBA include equitably accounting costs and benefits (United Nations Framework Convention on Climate Change [UNFCCC], "Assessing the Costs and Benefits of Adaptation Options: An Overview of Approaches" [2011], https://unfccc.int/resource/docs/publications/pub_nwp_costs_benefits_adaptation.pdf) and valuing design flexibility, considering broader economic impacts (and not only project financials), and setting appropriate discount rates and time horizons.

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Alliance for National & Community Resilience

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American Society of Civil Engineers, Committee on Adaptation to a Changing Climate

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