SUSTAINABLE INFRASTRUCTURE SERIES

OVERVIEW

LIFELINES

The Resilient Infrastructure Opportunity

Stéphane Hallegatte
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Foreword

Resilient infrastructure is about people. It is about the households and communities for whom infrastructure is a lifeline to better health, better education, and a better livelihood. It affects people's well-being, their economic prospects, and their quality of life.

Resilient infrastructure is, in part, about bridges that can withstand more frequent or stronger floods, water pipes that can resist earthquakes, or electric poles that are sturdier in the face of more intense hurricanes. And it is also about making sure people will not lose their jobs because they cannot get to work, that they can get urgent medical care, and that their children can get to school.

In developing countries, infrastructure disruptions are an everyday concern. When infrastructure fails, it undermines businesses, job creation, and economic development. With rapidly growing populations and a changing climate increasing the frequency and intensity of natural hazards, the need to adapt and invest in resilience should be an urgent priority.

Disruption to infrastructure costs households and firms in low- and middle-income countries at least $390 billion a year, and the indirect effects place a further toll on households, businesses, and communities. It is typically caused by poor maintenance, mismanagement, and the natural hazards that are increasing due to climate change.

But there is good news. Around the world, there are many examples of investments that make infrastructure more resilient and more economically robust.

This report assesses, for the first time, the cost of infrastructure disruptions to low- and middle-income countries and the economic benefits of investing in resilient infrastructure. It examines four essential infrastructure systems: power, water and sanitation, transport, and telecommunications. And the report lays out a framework for understanding the ability of infrastructure systems to function and meet users' needs during and after natural shocks.

We find that the extra cost of building resilience into these systems is only 3 percent of overall investment needs. Thanks to fewer disruptions and reduced economic impacts, the overall net benefit of investing in the resilience of infrastructure in developing countries would be $4.2 trillion over the lifetime of new infrastructure. That is a $4 benefit for each dollar invested in resilience.

Finally, with a range of clearly defined recommendations, the report lays out how to unlock this $4.2 trillion opportunity. Rather

than just spending more, the focus is on spending better. The message for infrastructure investors, governments, development banks, and the private sector is this: Invest in regulations and planning, in the early stages of project design, and in maintenance. Doing so can significantly outweigh the costs of repairs or reconstruction after a disaster strikes.

There is no time to waste. With a rapidly changing climate, and large investments in infrastructure taking place in many countries, business as usual over the next decade would cost $1 trillion more. By getting it right, however, we can provide the critical infrastructure services—lifelines—that will spur sustained and resilient economic development.

Kristalina Georgieva
Chief Executive Officer
The World Bank

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Overview

From serving our most basic needs to enabling our most ambitious ventures in trade or technology, infrastructure services support our well-being and development. Reliable water, sanitation, energy, transport, and telecommunication services are universally considered to be essential for raising the quality of life of people. Access to basic infrastructure services is also a central factor in the productivity of firms and thus of entire economies, making it a key enabler of economic development. And in this time of rapid climate change and intensifying natural disasters, infrastructure systems are under pressure to deliver resilient and reliable services.

By one estimate, governments in low- and middle-income countries around the world are investing around $1 trillion—between 3.4 percent and 5 percent of gross domestic product (GDP)—in infrastructure every year (Fay et al. 2019).[1] Still, the quality and adequacy of infrastructure services vary widely across countries. Millions of people, especially in fast-growing cities in low- and middle-income countries, are facing the consequences of substandard infrastructure, often at a significant cost. Underfunding and poor maintenance are some of the key factors resulting in unreliable electricity grids, inadequate water and sanitation systems, and overstrained transport networks.

Natural hazards magnify the challenges faced by these already-strained and fragile systems. Urban flooding, for instance, is a reality for people around the world—from Amman, Buenos Aires, and Dar es Salaam to Jakarta and Mumbai. Often exacerbated by poor drainage systems, these floods cause frequent disruptions in transport and energy networks, which in turn affect telecommunications and other essential services. The lack of resilient sanitation systems also means that floods often spread dangerous waterborne diseases.

The disruption of infrastructure services is especially severe when considering more extreme natural shocks. For example, earthquakes damage port infrastructure and slow down local economies, as occurred in Kobe in 1995. Hurricanes wipe out electricity transmission and distribution systems, cutting people's access to electricity for months, as occurred in Puerto Rico in 2017. In these examples, many people who did not experience direct damage from the disaster still experienced impacts from infrastructure disruptions.

This report, *Lifelines: The Resilient Infrastructure Opportunity,* explores the resilience of four essential infrastructure systems: power, water and sanitation, transport, and telecommunications. All of these systems provide critical ser-

vices for the well-being of households and the productivity of firms, yet they are particularly vulnerable to natural hazards because they are organized in complex networks through which even small local shocks can propagate quickly. Making them more resilient—that is, better able to deliver the services people and firms need during and after natural shocks—is critical, not only to avoid costly damage but also to minimize the wide-ranging consequences of natural disasters for the livelihoods and well-being of people.

Building on a wide range of case studies, global empirical analyses, and modeling exercises, this report arrives at three main messages:

- *The lack of resilient infrastructure is harming people and firms.* Natural disasters cause direct damage to power generation and transport infrastructure, costing about $18 billion a year in low- and middle-income countries. This damage is straining public budgets and reducing the attractiveness of these sectors for private investors. But natural hazards not only damage assets, they also disrupt infrastructure services, with significant impacts on firms and people. Altogether, infrastructure disruptions impose costs between $391 billion and $647 billion a year on households and firms in low- and middle-income countries. These disruptions have a wide range of causes, including poor maintenance, mismanagement, and underfunding. But case studies suggest that natural hazards typically explain 10 percent to 70 percent of the disruptions, depending on the sector and the region.
- *Investing in more resilient infrastructure is robust, profitable, and urgent.* In low- and middle-income countries, designs for more resilient assets in the power, water and sanitation, and transport sectors would cost between $11 billion and $65 billion a year by 2030—an incremental cost of around 3 percent compared with overall investment needs. And these costs can be reduced by looking at *services*, not just *assets*, and making infrastructure service *users*—households and supply chains—better able to manage disruptions. This report finds that investing $1 in more resilient infrastructure is beneficial in 96 percent of thousands of scenarios exploring possible future socioeconomic and climate trends. In the median scenario, the net benefit of investing in more resilient infrastructure in low- and middle-income countries is $4.2 trillion, with $4 in benefit for each $1 invested. Climate change makes action on resilience even more necessary and attractive: on average, it doubles the net benefits from resilience. And because large investments in infrastructure are currently being made in low- and middle-income countries, the median cost of one decade of inaction is $1 trillion.
- *Good infrastructure management is the necessary basis for resilient infrastructure, but targeted actions are also needed.* Unfortunately, no single intervention will make infrastructure systems resilient. Instead, a range of coordinated actions will be required. The first recommendation is for countries to get the basics right—proper planning, operation, and maintenance of their assets—which can both increase resilience and save costs. However, good design and management alone are not enough to make infrastructure resilient, especially against rare and high-intensity hazards and long-term trends like climate change. To address these issues, this report offers four additional recommendations: define institutional mandates and strategies for infrastructure resilience; introduce resilience in the regulations and incentive systems of infrastructure sectors, users, and supply chains; improve decision making through data, tools, and skills; and provide appropriate financing—especially for risk-informed master plans, asset design, and preparedness. Actions on these issues can be highly cost-effective and transformational, but they can nevertheless be challenging to fund in many poor countries, making them priorities for support from the international community.

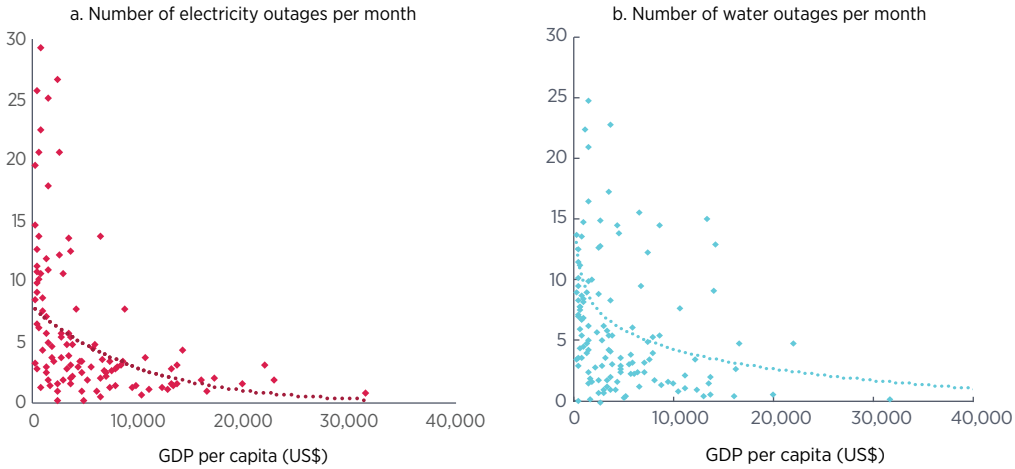
INFRASTRUCTURE DISRUPTIONS ARE A DRAG ON PEOPLE AND ECONOMIES

This report begins by investigating how infrastructure disruptions—regardless of their origin—affect people and firms. The frequency of these disruptions is generally closely linked to the level of economic development, as shown in figure O.1 using GDP per capita as a proxy and electricity and water outages from the World Bank's Enterprise Surveys. Disruptions cost people both indirectly, through their effects on the productivity of firms, and directly, through their effects on households' consumption and well-being.

Infrastructure disruptions cost firms more than $300 billion per year

Unreliable infrastructure systems affect firms through various impacts (table O.1). Most visible are the direct impacts: a firm relying on water to cool a machine must halt production during a dryout; a restaurant with an electric

FIGURE O.1 Poorer countries are hit hardest by inadequate infrastructure



Source: Rentschler, Kornejew, et al. 2019, based on the World Bank's Enterprise Surveys.
Note: Panels a and b show the latest available survey data for 137 countries, but none older than 2009. Panel a only shows countries with up to 30 outages a month. Eight countries (all with GDP per capita below $9,000) report between 30 and 95 outages a month.

TABLE O.1 Disrupted infrastructure services have multiple impacts on firms

Sector	Direct impacts	Coping costs	Indirect impacts
Power	• **Reduced utilization rates ($38 billion a year)** • **Sales losses ($82 billion a year)**	• **Generator investment ($6 billion a year)** • **Generator operation costs ($59 billion a year)**	• Higher barriers to market entry and lower investment • Less competition and innovation due to lack of small and new firms • Bias toward labor-intensive production • Inability to provide on-demand services and goods • Diminished competitiveness in international markets
Water	• **Reduced utilization rates ($6 billion a year)** • Sales losses	• Investment in alternative water sources (reservoirs, wells)	
Transport	• **Reduced utilization rates ($107 billion a year)** • Sales losses • Delayed supplies and deliveries	• Increased inventory • More expensive location choices, for example, in proximity to clients or ports	
Telecommunications	• Reduced utilization rates • Sales losses	• Expensive location choices close to fast Internet	

Source: Rentschler, Kornejew, et al. 2019.
Note: Highlighted in bold are the impacts for which original estimates are presented in this section. Estimates cover low- and middle-income countries.

stove cannot cook meals without power. Disruptions leave production capacity unused, reduce firms' sales, and delay the supply and delivery of goods. Firms also incur costs for coping with unreliable infrastructure, such as for backup power generation or water storage. The indirect impacts of disruptions are less immediate. They include effects on the long-term investment and strategic decisions of firms and on the composition, competition, and innovation of industries. Together, these effects figure in an economy's ability to generate wealth and in its international competitiveness (for details, see Braese, Rentschler, and Hallegatte 2019).

Using a set of microdata on about 143,000 firms, it is possible to estimate the monetary costs of infrastructure disruption for firms in 137 low- and middle-income countries, representing 78 percent of the world population (map O.1).[2] These data are used to assess the impact of infrastructure disruptions on the capacity utilization rates of firms—that is, to compare the actual output of firms with the maximum output they can achieve using all of their available resources—which is a good metric for firms' performance.

The data reveal utilization losses from power, water, and transport disruptions of $151 billion a year. (Unfortunately, a similar estimate for telecommunications is not possible because of a lack of data.) In addition, firm data reveal sales losses from electricity outages of $82 billion a year and additional costs of self-generating electricity of $65 billion a year. Although these figures highlight the significance of unreliable infrastructure, they constitute lower-bound estimates of the global costs of outages because neither all countries nor all types of impacts are covered in this analysis.

Infrastructure disruptions' direct impacts on people are worth at least $90 billion per year

Unreliable infrastructure services negatively affect the welfare of households. Frequent power outages limit the ability of households to engage in productive, educational, and recreational activities (Lenz et al. 2017). In South Asia, Zhang (2019) finds that long power outages are associated with a decrease in both per capita income and women's labor force participation, probably because the lack of electricity is associated with an increase in the time needed for domestic work (figure O.2). Studies also identify a strong and consistent relationship between water outages and health impacts. In the Democratic Republic of Congo, suspected cholera incidence rates increased 155 percent after one day of water disruption, compared with the incidence rate following optimal water provision (Jeandron et al. 2015).

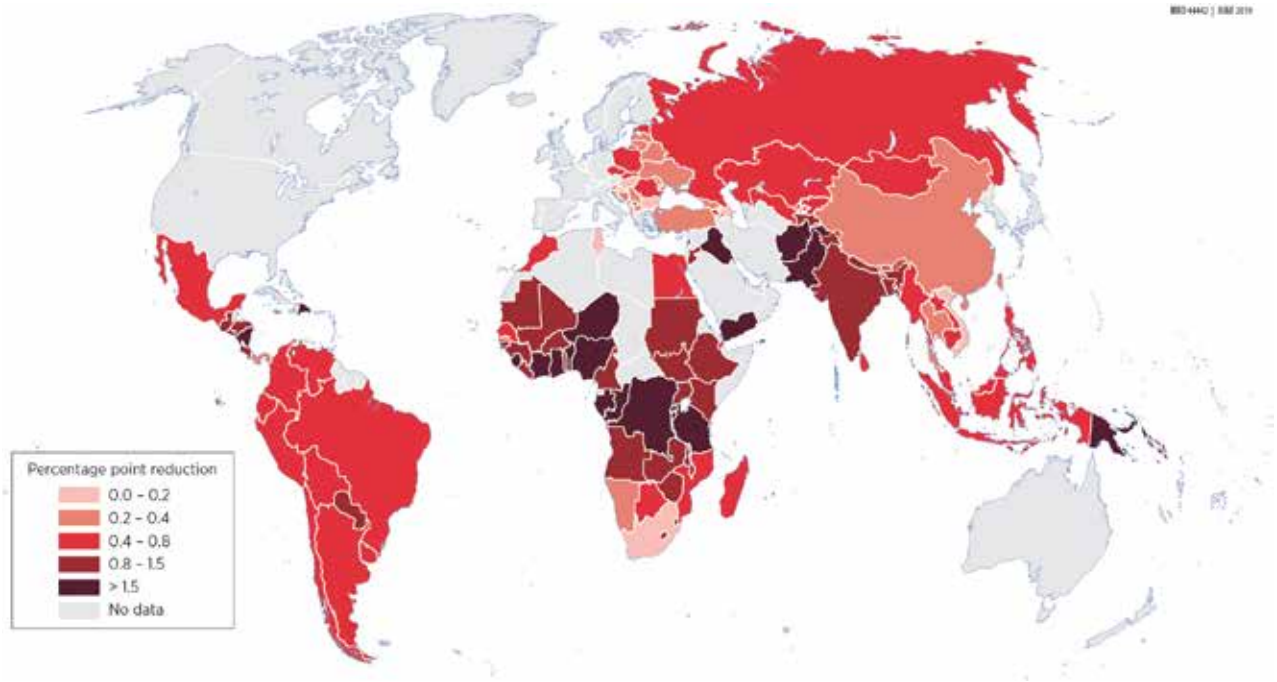
Infrastructure disruptions have many impacts on households, and estimating the global cost is difficult (table O.2). For this analysis, lower and upper bounds were established for power and water outages, based on studies assessing the willingness of households to pay to prevent such outages (see details in Obolensky et al. 2019). For power outages, the estimates range between 0.002 percent and 0.15 percent of GDP a year for low- and middle-income countries, which corresponds to between $2.3 billion and $190 billion.[3] In total, water interruptions are estimated to cost between 0.11 percent and 0.19 percent of GDP each year, which corresponds to a range of from $88 billion to $153 billion. Waterborne diseases stemming from an intermittent water supply are estimated to cause medical treatment costs and lost incomes between $3 billion and $6 billion a year. However, these results are highly uncertain because of differences in methodologies and contexts. Similar assessments of the transport and telecommunications sectors were not possible due to data constraints.

Natural shocks are among the leading causes of infrastructure disruptions

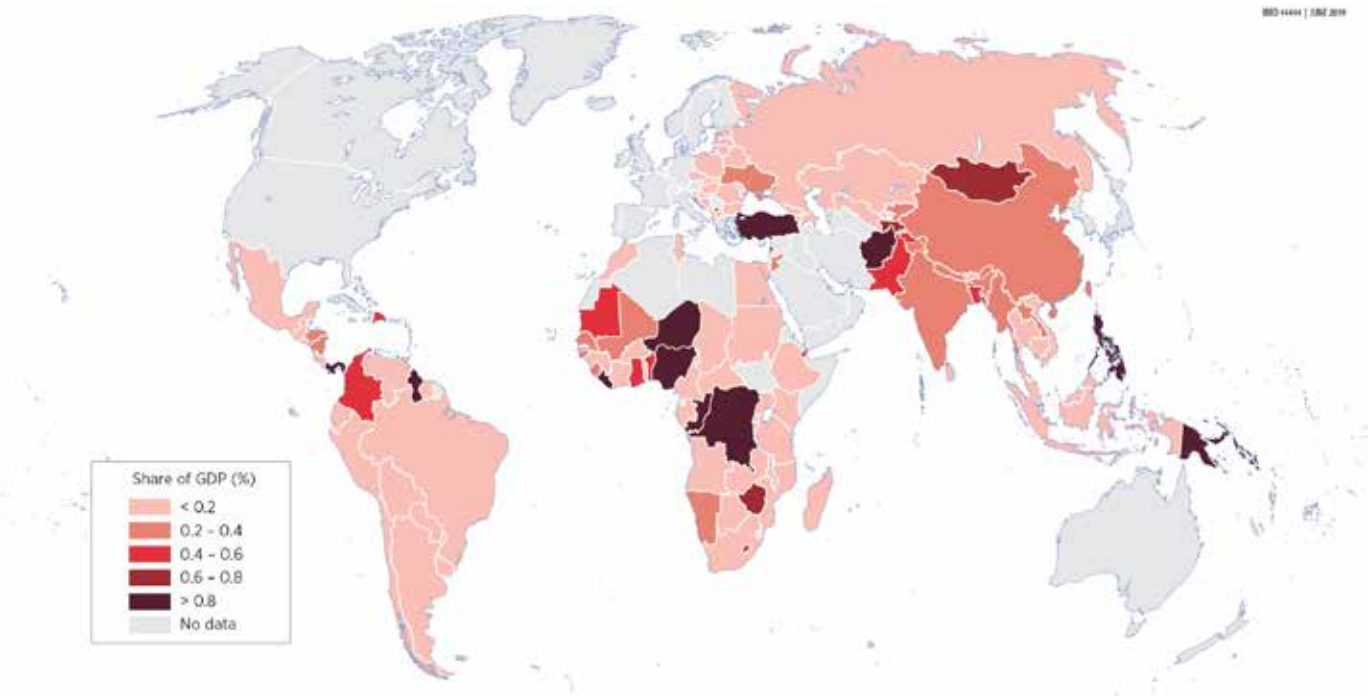
Taken together, the cost of infrastructure disruptions ranges from $391 billion to $647 billion in the low- and middle-income countries for which data are available and for the types

MAP O.1 Africa and South Asia bear the highest losses from unreliable infrastructure

a. Countrywide average utilization rate losses from disruptions in electricity, water, and transport infrastructure

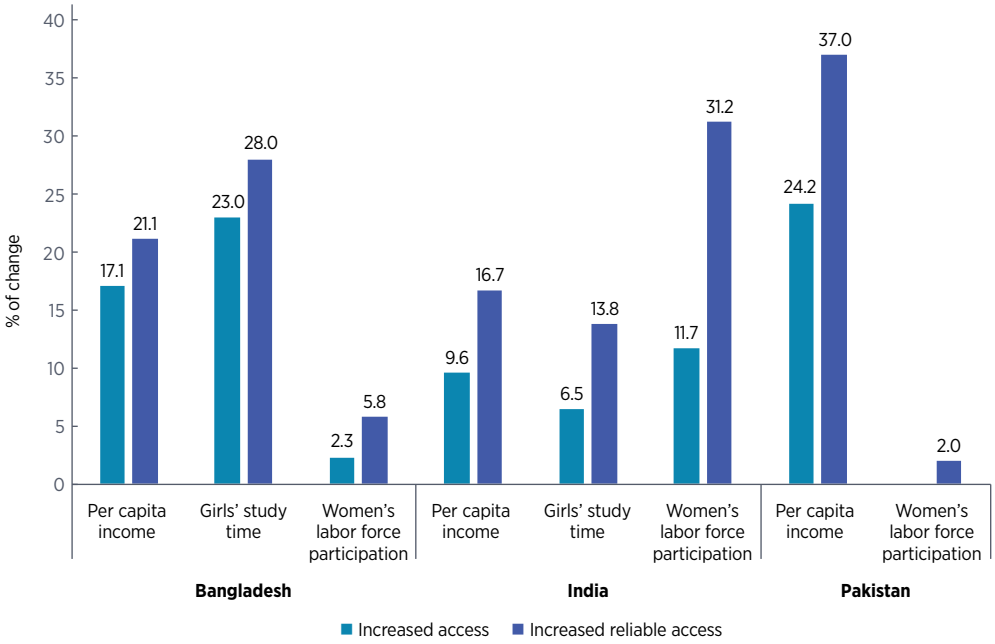


b. Additional costs of firms' backup electricity generation as % of GDP, including up-front investments and additional operating costs



Source: Rentschler, Kornejew, et al. 2019.

FIGURE O.2 Reliable access to electricity has more favorable effects on income and social outcomes than access alone in Bangladesh, India, and Pakistan



Source: Zhang 2019.
Note: Estimates are based on household surveys in Bangladesh, India, and Pakistan.

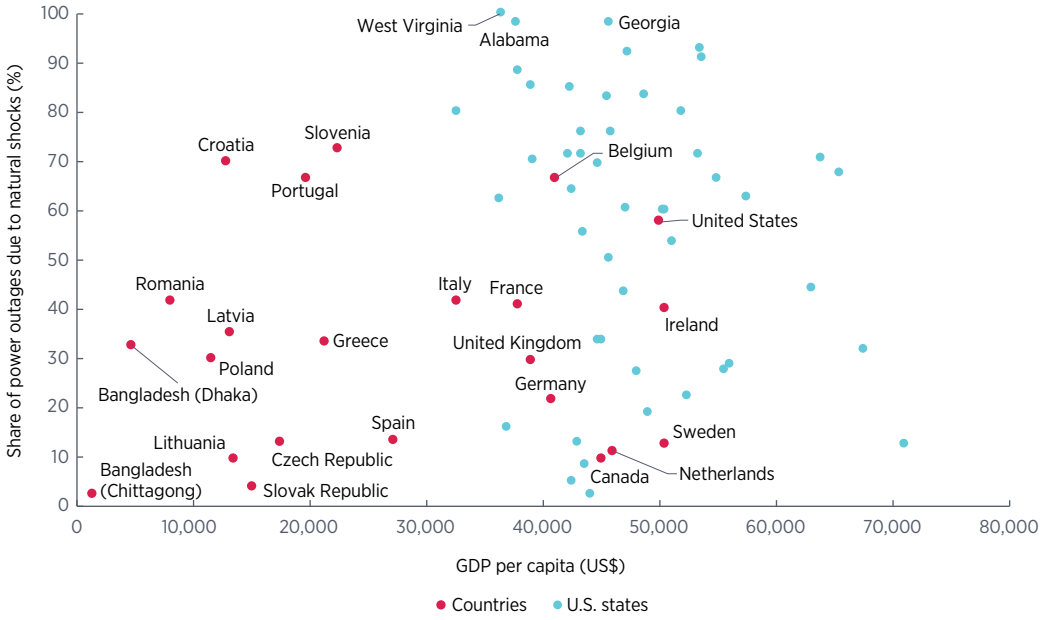
TABLE O.2 Disrupted infrastructure services have multiple impacts on households

Sector	Direct impacts	Coping costs	Indirect and health impacts
Power	• Diminished well-being • Lower productivity of family firms **Willingness to pay to prevent outages: between $2.3 billion and $190 billion a year**	• Generator investments • Generator operation costs	• Higher mortality and morbidity (lack of access to health care, air-conditioning during heat waves, or heat during cold spells)
Water	• Diminished well-being and loss of time **Willingness to pay to prevent outages: between $88 billion and $153 billion a year**	• Investment in alternative water sources (reservoirs, wells, water bottles)	• Higher incidence of diarrhea, cholera, and other diseases **Medical costs and missed income: between $3 billion and $6 billion a year**
Transport	• Greater congestion and loss of time • Higher fuel costs	• Higher cost of alternative transport modes	• Air pollution and health impacts • Constrained access to jobs, markets, services • People forced to live close to jobs, possibly on bad land
Telecommunications	• Diminished well-being		• Inability to call emergency services

Note: Highlighted in bold are the impacts for which original estimates are presented in this section. Estimates cover low- and middle-income countries.

of impacts that can be quantified. Even though these estimates are incomplete, they highlight the substantial costs that unreliable infrastructure impose on people in low- and middle-income countries. But what role do natural hazards play in these disruptions? While it is impossible to answer this question globally and for all sectors, many case studies document the role of natural hazards in infrastructure disruptions.

FIGURE O.3 Natural shocks explain a significant fraction of power outages

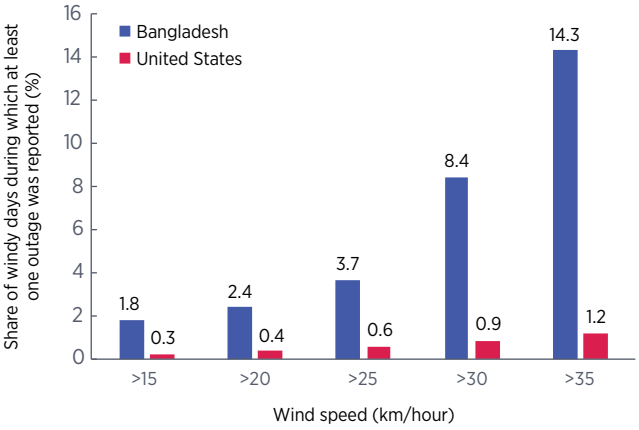


Source: Rentschler, Obolensky, and Kornejew 2019.

In the power sector, natural hazards—in particular, storms—are a major cause of electricity supply disruptions, as shown in figure O.3. In Belgium, Croatia, Portugal, Slovenia, and the United States, they are responsible for more than 50 percent of all outages. By contrast, in Bangladesh, natural shocks account for a smaller share of power outages—not because energy systems are more resilient, but because system failures and nonnatural factors are so frequent that energy users experience daily outages. But this figure also underestimates the role of natural hazards because outages caused by natural hazards tend to be longer and geographically larger than other outages. In Europe between 2010 and 2017, natural hazard–induced outages lasted 409 minutes on average, making them almost four times as long as outages caused by nonnatural causes. And in Bangladesh in 2007, Tropical Storm Sidr caused the largest outage in national history: all 26 power plants tripped and failed, leaving customers without power for up to a week (Rentschler, Obolensky and Kornejew 2019).

In many low- and middle-income countries, natural shocks are responsible for a small fraction of power outages, although this does not mean that resilience is not an issue. Indeed, power systems are more vulnerable to natural shocks in poorer countries than in richer countries, and natural hazards can be responsible for a large number of disruptions. In the power sector, aging equipment, a lack of maintenance, rapid expansion of the grid, and insufficient generation capacity are all factors that reduce the reliability of service in general, while also increasing vulnerability to natural shocks. For example, storms of the same intensity are more likely to cause outages in Bangladesh than in the United States (figure O.4). On a day with average wind speeds exceeding 35 kilometers per hour, electricity users in Bangladesh are 11 times more likely to experience a blackout than U.S. consumers. As a result of this vulnerability, in 2013 in Chittagong, Bangladesh, users experienced about 16 power outages due to storms alone. This number corresponds to only 4 percent of all outages experienced, yet it is already

FIGURE O.4 The vulnerability of the power network to wind is much higher in Bangladesh than in the United States

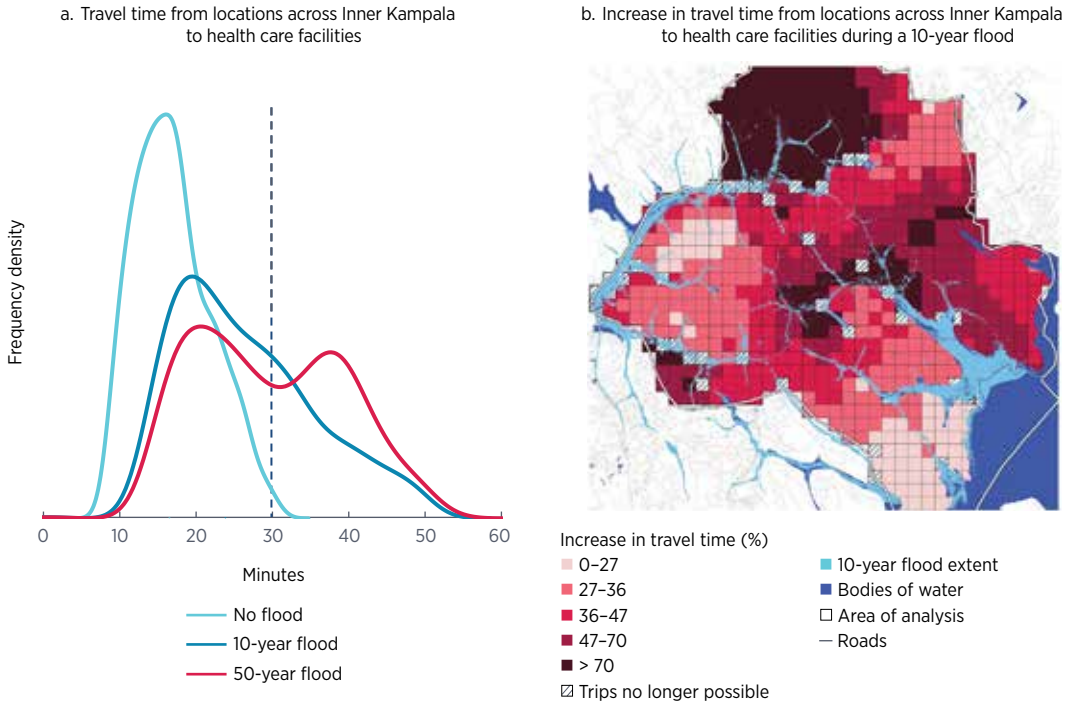


Source: Rentschler, Obolensky, and Kornejew 2019.
Note: Windy days are defined using different thresholds for recorded daily wind speeds. Wind speeds are obtained from the global ERA5 climate reanalysis model, which tends to underrepresent the highest local wind speeds.

more than 15 times higher than the average number of outages experienced by consumers in New York City.

In the transport sector, floods and other hazards disrupt traffic and cause congestion, taking a toll on people and firms in rich and poor countries alike. In Kampala, the impacts of floods on urban transport reduce people's access to a health care facility, according to an analysis undertaken for this report (Rentschler, Braese, et al. 2019) (figure O.5). A network analysis estimates that the mean travel time by car to a hospital from nearly all locations in Inner Kampala is less than 30 minutes. However, during a 10-year flood, disruption of the road network can increase travel times significantly, and about a third of persons living in

FIGURE O.5 Floods in Kampala severely restrict people's access to health care facilities



Source: Rentschler, Braese, et al. 2019.
Note: In panel a, the vertical line denotes the "golden hour" (the window of time that maximizes survival of a major health emergency), assuming that ambulances complete a return trip starting at a hospital. The curves show frequency densities that represent the distribution of travel times from all locations. The 10-year flood is the flood of a magnitude that occurs on average once every 10 years.

Inner Kampala would no longer be able to reach health facilities within the "golden hour"—a rule of thumb referring to the window of time that maximizes the likelihood of survival after a severe medical incident.

Such flood-related transport disruptions are costly for firms. The same network analysis estimates travel times between some 400 firms as a proxy for the impact of floods on interfirm connectivity and local supply chains. A moderate flood in Kampala increases the average travel time between firms by 54 percent. A significant number of firms are affected even more severely, with more than a quarter of firms facing an increase in average travel time of between 100 percent and 350 percent. As roads are flooded, people are unable to reach their workplace, and firms wait in vain for supplies, miss their deliveries, and lose sales.

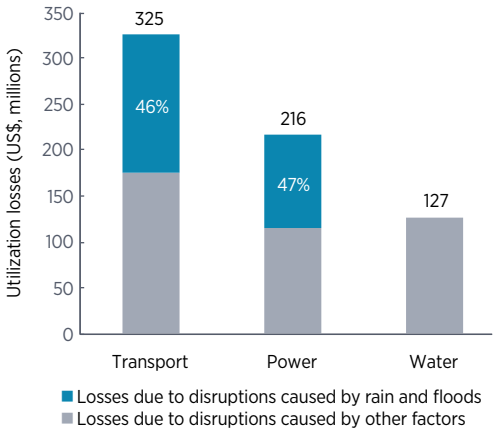
In the water sector, assets and services are also affected by natural hazards, even in the absence of physical damage to assets. The severe landslides that occurred in Lima in March 2017, interrupted the water supply for four days, as the city's river filled with mud. The main water treatment plant could not handle the resulting turbidity and had to shut down (Stip et al. 2019).

In the telecommunications sector, in December 2006, the Great Hengchun Earthquake on the island of Taiwan, China, and in the Luzon Strait was one of the severest examples of disruptions to the submarine cable systems on which international communications networks depend. Submarine landslides caused 19 breaks in seven cable systems, requiring repairs that were carried out over 49 days. Meanwhile, traffic was quickly rerouted using undamaged infrastructure, but the pressures on it resulted in a lower quality of service and delays. Internet connectivity in the region was seriously affected, and financial services and the airlines and shipping industries were significantly hurt (Sandhu and Raja 2019).

Although it is agreed that disruptions from natural hazards represent a significant cost for firms and households, local studies are needed to provide a detailed assessment. To support such an assessment, a survey was developed and piloted in Tanzania for a sample of 800 firms across the country. It found that Tanzanian firms are incurring utilization losses of $668 million a year from power and water outages and transport disruptions, which is equivalent to 1.8 percent of the country's GDP (figure O.6). Power alone is responsible for losses of $216 million a year, and 47 percent of these losses are solely due to power outages that can be attributed to rain and floods (equivalent to $101 million, or 0.3 percent of GDP). As for transport disruptions, about 46 percent of utilization losses stem from disruptions caused by rain and floods (equivalent to $150 million, or 0.4 percent of GDP). But the survey does not find that rain and floods have a significant impact on the incidence of water supply disruptions.

In addition to these disruptions, natural hazards cause direct damage to infrastructure assets. This damage is critical, given that it burdens public infrastructure budgets and detracts from the attractiveness of the infrastructure sector for private investors. Based on a global risk assessment performed for this report,

FIGURE O.6 Tanzanian firms report large losses from infrastructure disruptions



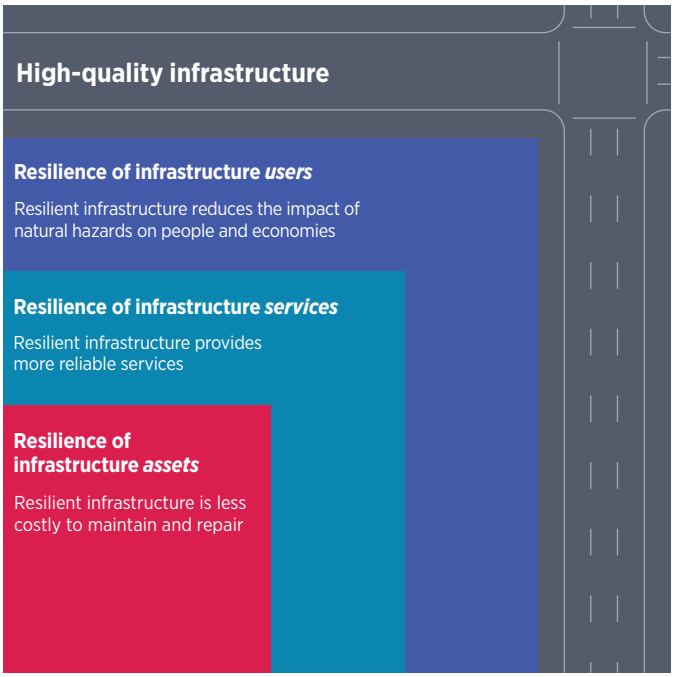
Source: Rentschler, Braese, et al. 2019.

power generation and transport infrastructure incur losses of $30 billion a year on average from natural hazards (about $15 billion each), with low- and middle-income countries shouldering about $18 billion of the total amount (Koks et al. 2019; Nicolas et al. 2019).

Although these numbers remain manageable on average and at the global level, losses can reach high values after extreme events. In some vulnerable countries, they are high enough to impede the provision of universal access to infrastructure services.

The severity of natural disasters is usually measured by the asset losses they provoke (Munich Re 2019; Swiss Re 2019). But the secondary consequences of direct asset losses on economic activities and output can often explain a large share of total disaster impacts, especially when infrastructure systems are affected (Hallegatte 2013; Hallegatte and Vogt-Schilb 2016). For example, Rose, Oladosu, and Liao (2007) estimate the total cost of a two-week blackout in Los Angeles at $2.8 billion—that is, 13 percent of the total economic activity during the two weeks. Colon, Hallegatte, and Rozenberg (2019) find that in Tanzania, the macroeconomic impact of a flood disruption in the transport sector increases nonlinearly with the duration of the disruption. A four-week disruption is, on average, 23 times costlier for households than a two-week disruption. Comprehensive risk assessments need to account for these secondary impacts and look beyond asset losses to inform disaster risk management investments and policies properly and to guide decision making on infrastructure design and operation.

FIGURE O.7 The resilience of infrastructure should be considered at several overlapping and complementary levels



MORE RESILIENT INFRASTRUCTURE ASSETS PAY FOR THEMSELVES

The resilience of infrastructure has three levels (figure O.7):

- *Resilience of infrastructure assets*. In the narrowest sense, resilient infrastructure refers to assets such as roads, bridges, cellphone towers, and power lines that can withstand external shocks, especially natural hazards. Here, the benefit of more resilient infrastructure is that it reduces the life-cycle cost of assets.
- *Resilience of infrastructure services.* Infrastructure systems are interconnected networks, and the resilience of individual assets is a poor proxy for the resilience of services provided at the network level. For infrastructure, a systemic approach to resilience is preferable. At this level, the benefit of more resilient infrastructure is that it provides more reliable services.
- *Resilience of infrastructure users.* Eventually, what matters is the resilience of users. Infrastructure disruptions can be catastophic or benign, depending on whether users—including people and supply chains—can cope with them. At this level, the benefit of more resilient infrastructure is that it

reduces the total impact of natural hazards on people and economies.

The resilience of infrastructure is one of the many determinants of high-quality infrastructure. However, integrating resilience in the design and implementation of infrastructure investments not only helps to manage natural shocks but also complements the cost-effectiveness and quality of infrastructure services more generally.

Building more resilient infrastructure assets in exposed areas is cost-effective

The additional up-front cost of more resilient infrastructure assets ranges from negative to a doubling of the construction cost, depending on the asset and the hazard. Interventions to make assets more resilient include using alternative materials, digging deeper foundations, elevating assets, building flood protection around the asset, or adding redundant components.

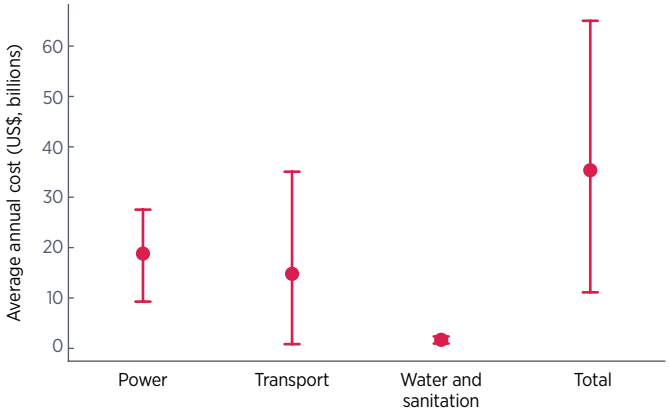
How much would it cost to implement these technical solutions? This report tackles this question with an analysis that begins with the estimates by Rozenberg and Fay (2019) of how much low- and middle-income countries would have to spend on infrastructure to achieve their development goals. The analysis then asks how much those estimates would change if infrastructure systems were designed and built in a more resilient manner (using one set of technical options from Miyamoto International 2019). Note that the solutions assessed here do not guarantee that assets cannot be damaged by natural hazards and do not include all possible options to reduce risks. Many high-income countries like Japan implement technical solutions that go beyond—and are more expensive than—the set of solutions considered in this analysis.

Overall, the incremental cost of building the resilience of infrastructure assets in low- and middle-income countries is small, provided the right data, risk models, and decision-making methods are available. Improving the resilience of only the assets that are exposed to hazards would increase investment needs in power, water and sanitation, and transport by between $11 billion and $65 billion a year (figure O.8). Although not negligible, this range represents only 3 percent of infrastructure investment needs and less than 0.1 percent of the GDP of low- and middle-income countries. It would, therefore, not affect the current affordability challenges that countries face.

However, making infrastructure more resilient by strengthening assets is realistic only if the appropriate data on the spatial distribution of natural hazards are available. Without information on which locations are exposed to hazards, strengthening the whole system would cost 10 times more, between $120 billion and $670 billion, which suggests that the value of hazards data is orders of magnitude higher than the cost of producing the information.

What are the returns on investments for making exposed infrastructure more resilient to natural disasters? The uncertainty pertaining to the cost of infrastructure resilience and the benefits in terms of both avoided repairs and

FIGURE O.8 The incremental cost of increasing the resilience of future infrastructure investments depends on the spending scenario but remains limited in all cases



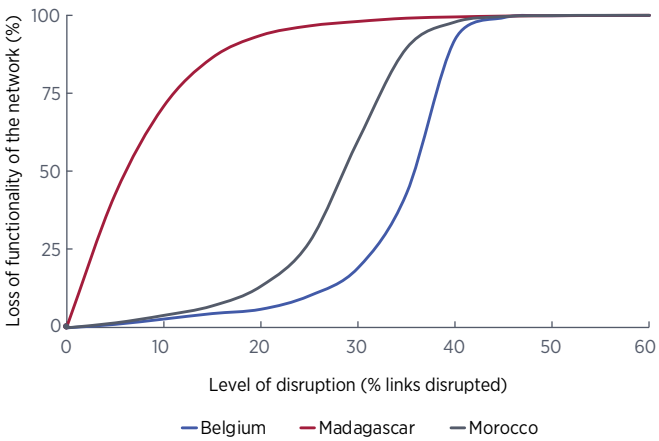
Source: Hallegatte et al. 2019.
Note: This figure shows the incremental annual capital cost for more resilient infrastructure for 2015–30. The range comes primarily from the uncertainty on how much will be invested on infrastructure during the period (and on the technologies chosen).

disruptions for households and firms make it difficult to provide one single estimate for the benefit-cost ratio of strengthening exposed infrastructure assets. However, a set of 3,000 scenarios (which covers the uncertainty of all parameters of the analysis) can be used to explore the costs and benefits of making infrastructure more resilient.

The analysis shows that, despite the uncertainty, investing in more resilient infrastructure is clearly a cost-effective and robust choice. The benefit-cost ratio is higher than 1 in 96 percent of the scenarios, larger than 2 in 77 percent of them, and higher than 6 in 25 percent of them (Hallegatte et al. 2019). The net present value of these investments, over the lifetime of new infrastructure assets, exceeds $2 trillion in 75 percent of the scenarios and $4.2 trillion in half of them. Moreover, climate change makes the strengthening of infrastructure assets even more important. Without climate change, the median benefit-cost ratio would be equal to 2, but it doubles when climate change is considered.

The urgency of investing in better infrastructure is also evident. With massive investment in infrastructure taking place in low- and middle-income countries, the stock of low-resilience assets is growing rapidly, increasing future costs of natural hazards and climate change. In 93 percent of the scenarios, it is costly to delay action from 2020 to 2030—and the median cost of a decade of inaction is $1 trillion.

FIGURE O.9 Belgium's and Morocco's transport systems can absorb much larger road disruptions than Madagascar's



Source: Rozenberg et al. 2019b.

From resilient infrastructure assets to resilient infrastructure services

Making assets more resistant is not the only option for building resilience. Expansion of the analysis from infrastructure *assets* to infrastructure *services* reveals that the cost of resilience can be reduced further by working at the network and system level—looking at criticality, redundancy, diversification, and nature-based solutions as additional options.

To illustrate the role of networks in infrastructure system resilience, a study conducted for this report quantifies *the resilience of transport networks,* defined as the ratio of the loss of functionality to the loss of assets (Rozenberg et al. 2019b). A resilient road network, such as the one in Belgium or Morocco, can lose many assets (such as road segments) without losing much functionality, whereas fragile networks with little redundancy, such as the one in Madagascar, become disfunctional even with slight damage (figure O.9). Similar approaches can be mobilized in water systems, where the typical methodology consists of mapping all components of a network and assessing the conditions under which they would fail, what the effects of those failures would be, and how they would affect service delivery.

Network effects create opportunities to strengthen the resilience of services and users at a limited cost, either by strengthening critical assets or by building in redundancy only where there are choke points (Rozenberg et al. 2019a). For transmission and distribution networks, for example, resilience is often built up through redundancy, which does not necessarily mean doubling or tripling key components of the network. A more effective approach is usually to create "ringed" or meshed networks that have multiple supply points for various nodes in the grid.

Diversification and decentralization also offer opportunities for more resilient services. The use of power generation with differentiated vulnerabilities (for example, hydropower, which is vulnerable to drought, versus solar and wind, which are vulnerable to strong winds) makes it more likely that a system will be able to maintain a minimum level of service. Multimodal transport systems that rely on nonmotorized modes and public transit are more resilient than systems that rely on private vehicles only. Distributed power systems using solar and batteries can harden a grid and make it more resilient. Minigrids and microgrids, because they do not rely on long-distance transmission wires, can provide useful backup generation in case of grid failure. During Hurricane Sandy, the Co-Op City microgrid in New York City was successfully decoupled from the main grid, and it supported consumers during outages in the wider network (Strahl et al. 2016).

Combining green and gray infrastructure can provide lower-cost, more resilient, and more sustainable infrastructure solutions (Browder et al. 2019). In New York City, 90 percent of water is from well-protected wilderness watersheds, making New York's water treatment process simpler than that of other U.S. cities (National Research Council 2000). According to Beck et al. (2018), without coral reefs the annual damage from coastal flooding would double worldwide. They estimate that Cuba, Indonesia, Malaysia, Mexico, and the Philippines benefit the most from their reefs, with annual savings of more than $400 million for each country. In Colombo, preserving the wetland system was found to be a cost-effective solution to reducing flooding in the city, even when accounting for land development constraints (Browder et al. 2019).

Limits to what is achievable in terms of strengthening also need to be considered. No infrastructure asset or system can be designed to cope with all possible hazards. And great uncertainty surrounds the probability and intensity of the most extreme events. As a result, infrastructure systems have to be stress-tested against a range of events to minimize the risk of catastrophic failures (Kalra et al. 2014). Such stress tests have two goals: (1) identify low-cost options that can reduce the vulnerability of infrastructure systems to extreme events, even quite unlikely ones, and (2) prepare for failure in terms of managing infrastructure systems (such as how to recover from a major failure) and in terms of supporting users (such as how to minimize impacts on hospitals). Running scenarios of failures is the first and most critical step in defining contingency plans.

Finally, sometimes the best way to make an infrastructure resilient is not to build it. Nicholls et al. (2019) find that coastal protection against storm surges and a rise in sea level would make economic sense only for about 22–32 percent of the world's coastlines through the 21st century. Thus, some communities may have to retreat gradually or use lower-cost or nature-based approaches to coastal defense. These communities are mostly in low-density areas where the costs of protection are too high to be affordable. In those areas, the best approach to resilience may be *not* to build new infrastructure. This approach, however, has to be complemented by a consistent strategy to manage retreat, while maintaining livelihoods and community ties.

From resilient infrastructure services to resilient users and economies

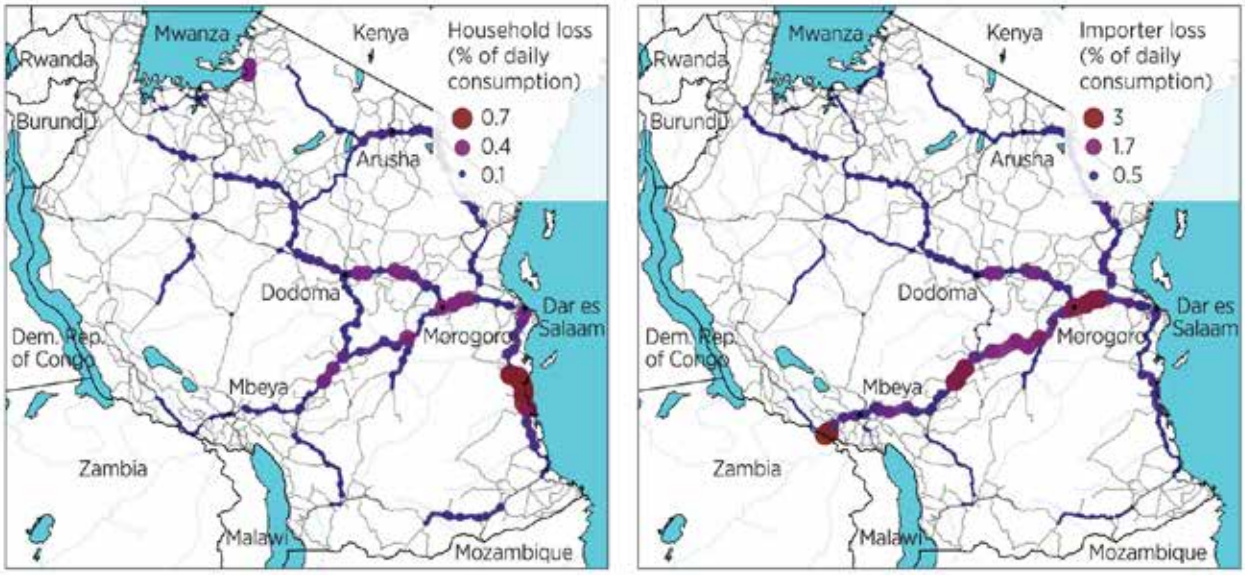
In some cases, it can be easier and cheaper to manage service interruptions than to prevent them. This report explores the role of the users of infrastructure services and how their actions can contribute to more resilient infrastructure systems.

Often, a first option for building resilience is to reduce demand by improving efficiency. In the face of growing populations and increasingly scarce water resources, a water utility can use demand management to reduce stress on the city's water supply. A recent example is Cape Town, which had to take drastic measures

MAP O.2 Investment priorities for Tanzania's transport network will depend on its supply chains

a. Impacts of disruption on households' consumption

b. Impacts of disruption on international clients



Source: Colon, Hallegatte, and Rozenberg 2019.
Note: The width of the line overlaying a given road is proportional to the impacts that a one-week disruption of that road would trigger. Impacts, measured in percentage of daily consumption, represent exceptional expenditures due to costlier transport and missed consumption due to shortages. Panel a shows these impacts for products consumed by households, and panel b shows these impacts for international buyers.

to avoid reaching "Day 0"—the day the city would run out of water. The demand management measures implemented by the city were extremely successful, reducing use by 40 percent between 2015 and 2018 and preventing what could have been a major socioeconomic crisis.

Understanding the needs and capacities of users helps utilities to target better where to invest and what part of the network to strengthen. A power distribution line to a hospital or a flood shelter is likely more important during and after an emergency than the average power line in a country. To investigate how criticality depends on users and supply chains, a study undertaken for this report combines a transport and a supply chain model to investigate the criticality of the transport network in Tanzania (Colon, Hallegatte, and Rozenberg 2019). Map O.2 shows the most critical assets in the transport sector for two supply chains and reveals that investment priorities for strengthening assets depend on which supply chains are considered most vulnerable or most important. For example, segments of the coastal trunk road, located about 200 km south of Dar-es-Salaam, are critical for domestic consumption but rather irrelevant for international trade. For trade, the road east of Morogoro appears as a priority. This segment accommodates large freight flows between the port of Dar es Salaam and landlocked countries, such as the Democratic Republic of Congo and Zambia.

When preventing disruptions is not possible or not affordable, firms have many options for improving their own resilience to disruptions. Larger inventories will protect them against transport issues. Generators and batteries will help them manage short power outages. Maintaining a diversity of suppliers, from both local and distant locations, is another powerful safeguard, especially against long disruptions. However, holding large inventories and managing multiple suppliers are financial burdens that involve significant transaction costs, making them most relevant for large firms. Because a

static supply chain will never be able to cope with a large-scale disaster and associated disruptions, adaptability is critical and should be embedded in business continuity plans (Christopher and Peck 2004; Sheffi 2005).

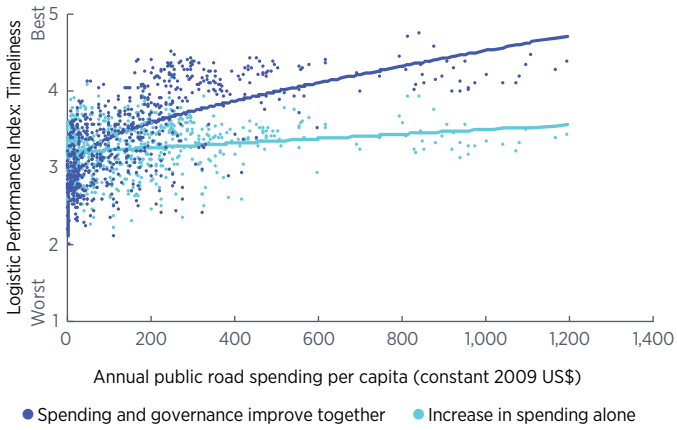
MAKING INFRASTRUCTURE MORE RESILIENT REQUIRES A CONSISTENT STRATEGY

In many countries, infrastructure disruptions are the symptoms of chronic shortcomings. Power outages occur every day, water supply is unreliable or unsafe, and congestion makes travel slow and unpredictable. In many places, these disruptions occur simply because infrastructure systems are not designed to keep up with ever-rising demand or because system failures are the result of poor asset management or maintenance. While natural hazards can exacerbate these issues, the majority of these disruptions reflect more fundamental challenges related to infrastructure design and management. This means that, to make infrastructure systems resilient, the first step is to make them reliable in normal conditions through appropriate infrastructure design, operation, maintenance, and financing.

Recommendation 1: Get the basics right

Underperforming infrastructure systems are explained largely by poor management and governance, according to a recent analysis of countries across the world (Kornejew, Rentschler, and Hallegatte 2019). Using the World Bank's Logistic Performance Index as a proxy, figure O.10 shows how the performance of the transport system depends on public spending on roads. Performance increases rapidly with spending per capita, but only if the quality of governance improves in parallel (dark blue line). If the quality of governance remains unchanged (light blue line), increased spending only yields marginal improvements in transport system performance and is not cost-effective. Similar analyses yield similar findings for power and water systems.

FIGURE O.10 Spending more improves the reliability of the transport system, but only if governance improves as well



Source: Kornejew, Rentschler, and Hallegatte 2019.

Thus, poor governance of infrastructure systems is the first obstacle that needs to be tackled. If infrastructure is to be resilient to natural shocks, countries first need to get the basics right for infrastructure management, with the following three priority actions.

Action 1.1: Introduce and enforce regulations, construction codes, and procurement rules

Well-designed regulations, codes, and procurement rules are the simplest approach to enhancing the quality of infrastructure services, including their reliability and resilience. Effective enforcement in the infrastructure sector requires a robust legal framework, but also strong regulatory agencies to monitor construction, service quality, and performance and to reward or penalize service providers for their performance. Currently, many regulators lack the resources and capacity to enforce the existing construction codes.

Action 1.2: Create systems for appropriate infrastructure operation, maintenance, and postincident response

Improving maintenance and operations is a no-regret option (it generates benefits whatever happens in the future) for boosting the resilience of infrastructure assets while reduc-

ing overall costs. An analysis of member countries of the Organisation for Economic Co-operation and Development performed for this report suggests that each additional $1 spent on road maintenance saves $1.5 in new investments, making better maintenance a very cost-effective option (Kornejew, Rentschler, and Hallegatte 2019). An important tool for this purpose is infrastructure asset management systems, which include an inventory of all assets and their condition, as well as all of the strategic, financial, and technical aspects of the management of infrastructure assets across their life cycle. Such tools help to move toward an evidence-based and preventive maintenance schedule and away from a reactive patch-by-patch approach to maintenance.

Action 1.3: Provide appropriate funding and financing for infrastructure planning, construction, and maintenance

The quality of infrastructure services depends on many factors, from good planning to good maintenance, but each of these comes at a cost (figure O.11). If resources are insufficient to meet the need for any of these factors, the quality of infrastructure services is likely to suffer. Even if investment spending is appropriate, insufficient resources for planning, designing, or maintaining assets would result in low quality and reliability. Dedicated funds and budgetary allocations can be used to ensure that enough resources are available to meet different needs, especially for maintenance.

Implementing these three basic measures would contribute to more reliable infrastructure systems and establish a basic capacity to cope with natural hazards and climate change. But they would not be sufficient to achieve more ambitious objectives regarding resilience. Without targeted actions to strengthen resilience, infrastructure assets will not be able to cope with rarer events, such as hurricanes, river floods, or earthquakes. And without specific actions on climate change, these assets run the risk of being designed for the wrong climate and environmental conditions. To build resilience to these evolving natural hazards, it is necessary to tackle four additional obstacles that are specific to the resilience challenge.

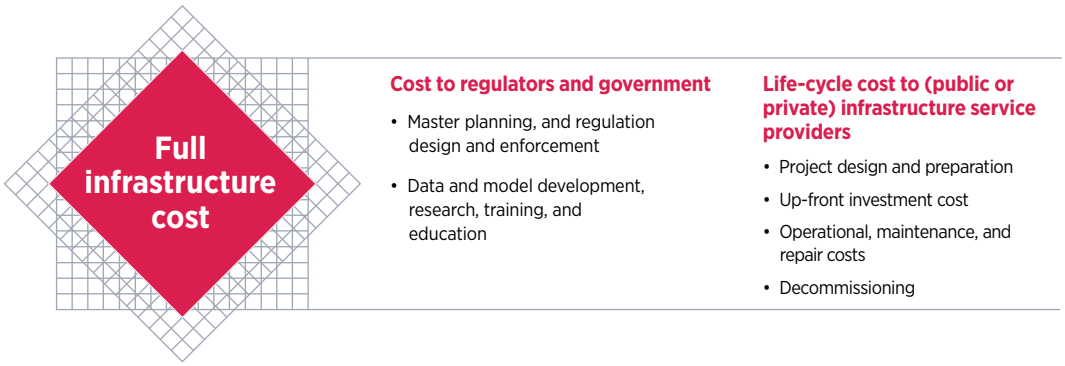
Recommendation 2: Build institutions for resilience

Political economy challenges and coordination failures impede the creation of a resilient infrastructure ecosystem. Governments, therefore, need to play a coordinating role (OECD 2019), with the following three priority actions.

Action 2.1: Implement a whole-of-government approach to infrastructure resilience, building on existing regulatory systems

Analysts agree that governments play a key role in ensuring the resilience of critical infrastructure and that they should adopt a whole-of-government approach (Renn 2008; Wiener and Rogers 2002; World Bank 2013). A common solution to improve the coordination of risk

FIGURE O.11 High-quality infrastructure requires providing for multiple funding needs



management across risks and across systems is to place an existing (or new) multiministry body in charge of information exchange, coordination, and possibly even implementation of risk management measures for infrastructure.

Action 2.2: Identify critical infrastructure and define acceptable and intolerable risk levels

Criticality analyses are an important tool for identifying the most important infrastructure assets and their vulnerability. Once the critical infrastructure assets and systems have been identified, governments need to define risk levels that are acceptable or intolerable. Each infrastructure sector can use these risk levels to design its own regulations and measures, ensuring consistency across systems. Definition of these risk levels needs to consider the local context, especially the resources that are available, and requires an open and participatory approach to ensure that risk management does not become an obstacle to development.

Action 2.3: Ensure equitable access to resilient infrastructure

Decisions regarding resilience cannot be driven by economic considerations alone. The strengthening of infrastructure resilience should be guided by a more complete assessment of the potential risks and impacts of disruptions, especially for vulnerable and marginalized population groups. New approaches enable more comprehensive assessments of spatial priorities. For example, estimates of *well-being losses* or *socioeconomic resilience* provide a balanced assessment of the impacts of natural disasters on poor and rich households (Hallegatte et al. 2016; Walsh and Hallegatte 2019).

Recommendation 3: Include resilience in regulations and incentives

A third obstacle to more resilient infrastructure is that public and private decision makers tend to have few incentives to avoid disruptions. Too often, they only consider lower repair costs when deciding on investments in resilience; they rarely consider the full social cost of infrastructure disruptions. Therefore, governments need to include resilience in a consistent set of regulations and financial incentives to align the interests of infrastructure service providers with the interests of the public (figure O.12), with the following three priority actions.

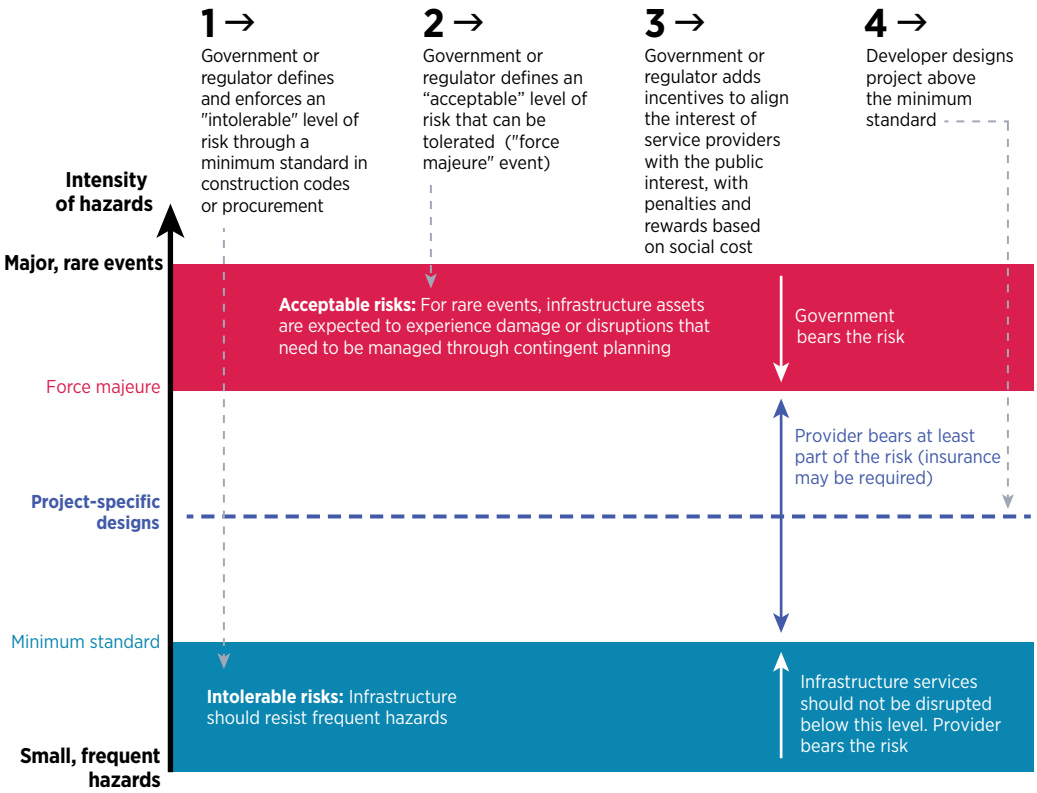
Action 3.1: Consider resilience objectives in master plans, standards, and regulations and adjust them regularly to account for climate change

Standards and regulations need to account for a range of factors, including climate conditions, geophysical hazards, environmental and socioeconomic trends, local construction practices, and policy priorities. They also need to be revised more regularly than is the case today to consider climate change and other long-term trends (Vallejo and Mullan 2017). In addition, governments can use regulations to strengthen the resilience of specific users of infrastructure services, not just providers. For example, hospitals could be required to maintain backup generators, batteries, and water tanks. And firms could be required to prepare business continuity plans to minimize the economic cost of disasters and infrastructure disruptions.

Action 3.2: Create financial incentives for service providers to promote resilient infrastructure services

Rewards and penalties can be used as incentives for service providers to go beyond the mandatory standards and implement cost-effective solutions to improve resilience (Pardina and Schiro 2018). The Australian Energy Regulator established the Service Target Performance Incentive Scheme, which includes penalties and rewards calibrated according to how willing consumers are to pay for improved service. Another example is payment-for-ecosystem-services schemes, which promote the use of nature-based solutions to increase resilience. In Brazil, water users pay a fee to the local water company that local watershed committees use for watershed maintenance and reforestation (Browder et al. 2019).

FIGURE O.12 Creating the right incentives for infrastructure service providers requires a consistent set of regulations and financial incentives



Action 3.3: Ensure that infrastructure regulations are consistent with risk-informed land use plans and guide development toward safer areas

Since infrastructure investments influence spatial development patterns, they can influence people's exposure to natural hazards. To ensure that new infrastructure contributes to the resilience of users, regulations should be aligned with risk-informed land use and urbanization plans. And the choice of infrastructure localizations needs to account for the potential investments that a new infrastructure asset will attract and the implications for resilience. Even better, infrastructure localization choices can be used to support the implementation of land use planning and promote low-risk spatial development.

Recommendation 4: Improve decision making

Even if regulators and providers of infrastructure services have the right incentives to build more resilient infrastructure systems, they often lack access to data and tools, as well as the skills and competencies they need to make good decisions. Governments, therefore, need to help all stakeholders to improve their decision making, with the following three priority actions.

Action 4.1: Invest in freely accessible natural hazard and climate change data

Investments in risk data and models (such as hydrological models, maps of flood hazards, digital elevation models, and inventories of infrastructure assets) can have extremely high returns by improving the design and mainte-

nance of infrastructure assets. Producing digital elevation models for all urban areas in low- and middle-income countries would cost between $50 million and $400 million in total and make it possible to perform in-depth risk assessments for all new infrastructure assets, informing hundreds of billions in investments per year. However, such data have public goods characteristics that discourage private actors from investing in them and require public support. To be useful, risk and infrastructure data must be made available (and affordable) to infrastructure service providers and users. While privacy and security concerns can make it necessary to restrict access, it is preferable to make open access the default situation for hazard and infrastructure data and to create processes to restrict access for data proven to be too sensitive.

Action 4.2: Make robust decisions and minimize the potential for regret and catastrophic failures

Often, large uncertainties make it impossible to design "optimal" systems or assets. An alternative is to seek *robust* designs that yield good results across a wide range of futures, preferences, and worldviews, even if they may not be optimal for any particular future. Decision makers can identify robust strategies through systematic stress-testing of possible options for a variety of hazards and threats—even highly unlikely ones—to ensure that the residual vulnerabilities are acceptable and manageable. These stress tests can help to capture low-cost opportunities to build resilience to low-probability, high-consequence events and prevent catastrophic failures. They can also support the development of contingency plans for service providers and business continuity plans for users.

Action 4.3: Build the skills needed to use data and models and mobilize the know-how of the private sector

Even if infrastructure risk data and models are available to all those seeking to improve infrastructure resilience, their appropriate use requires skills that are not always available. Universities and research centers need to be supported so that they can offer training, develop new methodologies (or adapt them to the local context), and advise policy and decision makers. When public sector expertise is insufficient, bringing in the private sector—through direct procurement or public-private partnerships—can be a solution.

Recommendation 5: Provide financing

The fifth obstacle is linked to affordability and financing constraints. Increasing resilience can increase various components of the life-cycle cost of infrastructure, including the costs borne by the government or regulators or the costs borne by infrastructure providers (figure O.11).

At times, these costs can lead to *affordability* challenges, when resilience increases the full life-cycle cost of an asset or system. Solutions might include either an increase in funding (financed through higher taxes, user fees, or transfers) or a trade-off between the resilience and quantity of infrastructure services (such as fewer but safer roads). But more often, making infrastructure more resilient increases only the costs of design, construction, or maintenance, while decreasing other costs such as repairs, so that the overall life-cycle cost is reduced. The challenge in that case is linked to *financing*—that is, transforming annual revenues or budgets into the resources needed at each stage of the infrastructure project life cycle, with the following three priority actions.

Action 5.1: Provide adequate funding to include risk assessments in master plans and early project design

Even though hundreds of billions of dollars are invested in infrastructure every year, it remains difficult to mobilize resources for infrastructure-sector regulations, risk-informed master plans, infrastructure risk assessment, or early-stage project design. More resources tend to become

available when infrastructure projects are mature, but at this stage most strategic decisions have already been made, and most low-cost options to increase resilience are no longer available (such as changing the location of an asset or even the nature of the project). Supporting and funding these activities is highly cost-effective and can be transformational, especially in poorer countries, making them a priority for international aid and cooperation (World Bank 2018). Dedicated organizations and project preparation facilities, such as the Global Facility for Disaster Reduction and Recovery or the Global Infrastructure Facility, are already active in these domains, but they remain small compared with the magnitude of the needs.

Action 5.2: Develop a government-wide financial protection strategy and contingency plans

In the aftermath of a disaster, governments are typically required to raise significant financing for response and recovery measures. Several instruments are available to do so, including reserve funds or budget reallocation, contingent credit, or insurance or risk transfers. The choice of financial instruments is determined by the risks that need to be covered, the cost of the instrument, the speed of disbursement, and the transparency and predictability of the resources (Clarke and Dercon 2016; World Bank 2017). After a disaster, however, the availability of financial resources is only half of the story; just as important is the ability to deliver resources effectively and rapidly to where they are needed, including to the firms and households that are affected by infrastructure disruptions, even if they are not affected directly by the disaster. Financial instruments therefore need to be combined with contingency plans and flexible delivery mechanisms—if possible, building on existing instruments, such as social protection systems.

Action 5.3: Promote transparency to better inform investors and decision makers

One way to ensure that resilient infrastructure projects are adequately financed is to inform investors and decision makers about the risks associated with projects. Multiple international, regional, and national initiatives are seeking to make the physical risks associated with investments and assets more transparent. Examples include the work of the Task Force for Climate-Related Financial Disclosure, which recommends that firms and investors report on physical risks and how they are managed. To contribute to this trend, the World Bank Group is committed to developing a resilience rating system to inform investors about the resilience of their infrastructure investments and help them to select the most resilient projects.

In sum, as illustrated by these five recommendations and 15 actions (table O.3), no single measure can make infrastructure systems resilient. Instead, governments need to define and implement a consistent strategy—in partnership with all stakeholders, such as utilities, investors, business associations, and citizen organizations—to tackle the many obstacles to more resilient infrastructure systems. One common feature of these recommendations is a focus on the early stages of infrastructure system development—the design of regulations, the production of hazards data and master plans, or the initial stages of new infrastructure asset design. These early stages are when small investments can significantly improve the overall resilience of infrastructure systems and generate very large benefits. In poor countries, however, mobilizing resources to invest in these actions may be challenging, which makes targeted support from the international community necessary, transformational, and highly cost-effective.

Although these recommendations are aimed at making infrastructure more resilient,

TABLE O.3 Five recommendations to address the five obstacles to resilient infrastructure

Recommendation	Actions
1: Get the basics right	1.1: Introduce and enforce regulations, construction codes, and procurement rules 1.2: Create systems for appropriate infrastructure operation, maintenance, and postincident response 1.3: Provide appropriate funding and financing for infrastructure planning, construction, and maintenance
2: Build institutions for resilience	2.1: Implement a whole-of-government approach to resilient infrastructure, building on existing regulatory systems 2.2: Identify critical infrastructure and define acceptable and intolerable risk levels 2.3: Ensure equitable access to resilient infrastructure
3: Create regulations and incentives for resilience	3.1: Consider resilience objectives in master plans, standards, and regulations and adjust them regularly to account for climate change 3.2: Create economic incentives for service providers to offer resilient infrastructure assets and services 3.3: Ensure that infrastructure regulations are consistent with risk-informed land use plans and guide development toward safer areas
4: Improve decision making	4.1: Invest in freely accessible natural hazard and climate change data 4.2: Make robust decisions and minimize the potential for regret and catastrophic failures 4.3: Build the skills needed to use data and models and mobilize the know-how of the private sector
5: Provide financing	5.1: Provide adequate funding to include risk assessments in master plans and early project design 5.2: Develop a government-wide financial protection strategy and contingency plans 5.3: Promote transparency to better inform investors and decision makers

most of them tackle market or government failures that are responsible not only for less resilient infrastructure but also for less efficient, less inclusive, and costlier infrastructure. As a result, taking these actions will contribute to more than infrastructure resilience and help create more productive, livable, and inclusive societies.

NOTES

1. In this report, all dollar amounts are U.S. dollars, unless otherwise indicated.
2. The data set covers 137 countries representing 80 percent of the GDP of low- and middle-income countries, or 32 percent of global GDP. Due to data limitations, the exact country coverage varies for different analyses. For details, refer to chapter 2 and Rentschler, Kornejew, et al. (2019).
3. The estimates summarized in this paragraph cover up to 137 low- and middle-income countries, although the exact country coverage varies across infrastructure sectors due to data constraints. For details, refer to chapter 3 and Obolensky et al. (2019).

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