Well Maintained: Economic Benefits from More Reliable and Resilient Infrastructure

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Table of Contents

Acknowledgements 2

Figures 4

Tables 4

Boxes 4

Context and Overview 6

The problem: unreliable infrastructure services impair growth and well-being 7

- Infrastructure services disruptions affect people directly 7
- Infrastructure services disruptions make firms less productive and competitive 10
- Lack of maintenance contributes to a lack of reliability 12

This problem will not fix itself–action is necessary and increasingly urgent 16

- Higher incomes and increased spending alone will not solve the issue 16
- Economies will be increasingly vulnerable to infrastructure disruption 19
  - Increasingly complex and efficient supply chains make economies more dependent on infrastructure systems 19
  - New technologies, digitalization, and decarbonization increase the reliance on electricity 19
- Environmental degradation and climate change make infrastructure more vulnerable and more important 20
  - Natural hazards cause significant damage to infrastructure assets everywhere 20
  - Effect of climate change on resiliency of infrastructure 21
- Other environmental degradation increases the need for hard infrastructure 22

The solutions: Better assets, better maintenance, better response 24

- Improve governance quality in investment planning and design 25
- Extending asset life by using life-cycle costing, maintenance, operations, and repairs 28
- Approaches to improve maintenance and operations, including private sector contracting 30
- Using new technologies to improve efficiency of existing infrastructure 34

What synergies and trade-offs are there in a post-COVID recovery phase? 37

- Potential job creation from infrastructure construction and maintenance 37
- The opportunity to boost maintenance through public works programs 39
- The effect of financial constraints on resilience and technology decisions 42

Conclusion 43

References 45

Figures

Figure 1: Reliability of electricity benefits individuals more than access alone 9

Figure 2: Additional costs of firms' backup electricity generation as percentage of gross domestic product (GDP), including up-front investments and additional operating costs 12

Figure 3: The vulnerability of the power network to wind in Bangladesh and in the United States 14

Figure 4: Lower income countries experience lower quality of infrastructure services 17

Figure 5: Relation between transport resilience and public road spending per capita 18

Figure 6: Share of power outages caused by natural shocks and GDP 21

Figure 7: The incremental cost of increasing the resilience of future infrastructure investments depends on the spending scenario but remains limited in all cases 26

Figure 8: Trade-offs between building and maintaining public roads. 28

Figure 9: Employment creation for different types of work 39

Figure 10: Jobs created (in person-year) by $1 million in public spending, for new infrastructure assets (blue) and maintenance (yellow) 41

Figure 11: High-quality infrastructure requires providing for multiple funding needs 42

Tables

Table 1: Disrupted infrastructure services have multiple impacts on households 10

Table 2: Disrupted infrastructure services have multiple impacts on firms 11

Table 3: Employment generation on sample road contracts in Lebanon and Jordan 40

Boxes

Box 1: Preparing operation and maintenance strategies—example for hydropower 15

Box 2: Well-designed and maintained infrastructure minimizes environmental degradation. 27

Box 3: An increase in maintenance spending is critical to close the infrastructure gap 29

Box4: Fukuoka City, Japan—a life-cycle cost approach to extending asset life for a resilient water supply system 31

Box 5: Using performance-based contracting (PBC) to reduce water leakage in Vietnam 32

Box 6: Global Infrastructure Facility support to Ukraine's road asset management program and the role of the private sector 33

Box 7: G20 Riyadh InfraTech Agenda 35

Context and Overview

The report frames the World Bank's contribution to the G20's Policy Agenda under Italy's presidency on Infrastructure Maintenance and draws on several recent World Bank reports, including *Beyond the Gap* and *Lifelines*. Building on the World Bank's operational and analytical work, this report offers evidence that inadequate or deferred maintenance of infrastructure assets have costs and repercussions that affect the growth and well-being of people, firms, and economic systems as a whole. Regular maintenance is an essential contributor to infrastructure resilience. Further, this report highlights that more spending alone is not sufficient, unless it is accompanied by new approaches in planning, costing, and delivering maintenance, operations, and repairs. In doing so, the report draws lessons from private participation in infrastructure. Lastly, the report identifies synergies and trade-offs that come to play when pursuing infrastructure maintenance as the global economies enter the post-COVID recovery phase.

The Problem: unreliable infrastructure services impair growth and well-being

Infrastructure disruptions, from daily traffic accidents to major power outages, are an everyday concern in both developed and developing countries. Not only do infrastructure disruptions affect people's well-being and quality of life, but they also undermine businesses, job creation, and economic prospects. Resilient infrastructure, on the other hand, can be a lifeline to better health, better education, and better livelihoods, and is necessary to maintain economic development and prosperity.

Infrastructure services disruptions affect people directly

On the one hand, disruption of infrastructure affects households, which lose access to these services, e.g., safe drinking water, and professional, educational, or medical services. On the other hand, it affects businesses, which lack access to the necessary infrastructure to keep factories running, e.g., electrical grid, water supply, transportation, or communication services.

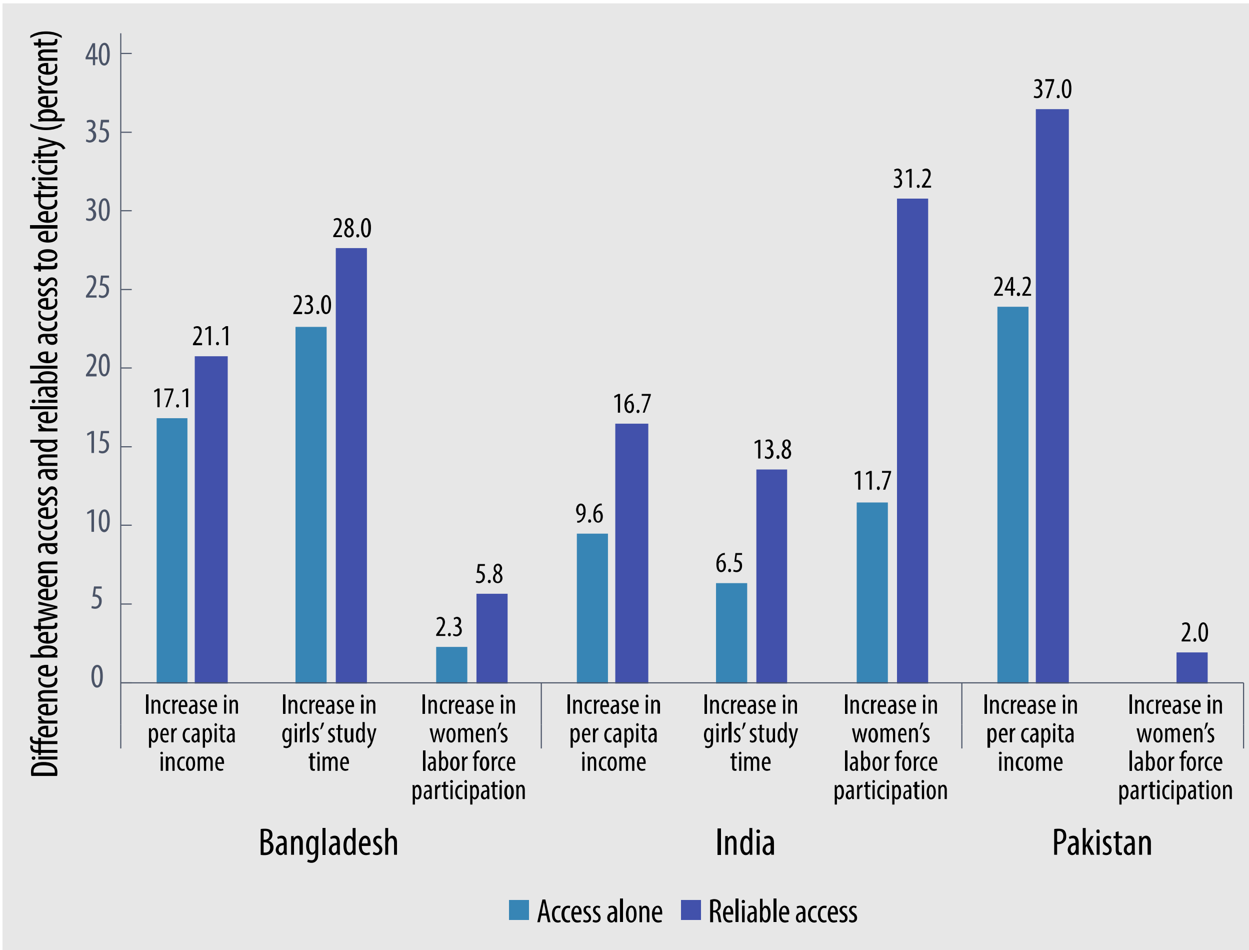
Access to reliable infrastructure is necessary to cover people's basic needs, and the effects of infrastructure disruptions on private households are multidimensional (Figure 1). For example:

- They affect people's lives directly by increasing the risk for disease and cutting people off from transportation or communication, and indirectly by limiting people's abilities to engage in productive, educational, and recreational activities (Lenz et al. 2017).
- Disruptions to water infrastructure can pose serious health threats: 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). Consistent access to electricity reduces the need to cook on open fires, which positively affects air quality (Ni et al. 2016).
- A lack of access to electricity is also associated with an increase in the time needed for domestic work. Because women are often in charge of domestic work, they suffer disproportionately from poor infrastructure services, which are found to reduce women labor participation.
- Children are also directly affected by unreliable infrastructure because they tend to rely on public transportation to get to and from school. Children are also particularly vulnerable to disease.

The direct impacts of unreliable infrastructure alone on people in low- and middle-income countries are estimated to amount to at least $90 billion per year (Hallegatte, Rentschler, and Rozenberg 2019). In particular, the cost of power outages for private households in low- and middle-income countries is estimated to run from $2.3 billion to $190 billion dollars a year (Rentschler et al. 2019).[1] The cost of water system disruptions ranges from $88 billion to $153 billion. Impacts on households in high-income countries are expected to be lower, in relative terms, because the frequency of outages is much smaller; however, a single outage can have very large impacts in high-income countries, where households tend to be highly dependent on infrastructure services (see, e.g., LaCommare et al. 2004).

[1] Estimates of willingness to pay are highly uncertain, as illustrated by the large range of values in the table. Uncertainty arises from methodological differences, but also from the non-linearity and context-specificity of welfare impacts of disruptions, which cannot be captured properly with available data.

Figure 1: Reliability of electricity benefits individuals more than access alone



Source: Zhang 2019.

Table 1: 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	• Generator investments • Generator operation costs	• Higher mortality and morbidity (lack of access to health care, air conditioning during heat waves, or heat during cold waves)
	• **Willingness to pay to prevent outages: between $2.3 billion and $190 billion a year**		
Water	• Diminished well-being and loss of time	• Investment in alternative water sources (reservoirs, wells, water bottles)	• Higher incidence of diarrhea, cholera, and other diseases
	• **Willingness to pay to prevent outages: between $88 billion and $153 billion a year**		**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 risky 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. The “willingness to pay” is defined as the amount households would be ready to pay to prevent all outages, and is expected to include the financial cost of the outages (e.g., buying water bottles during water outages) as well as the welfare, non-monetary, cost (e.g., time lost fetching water at a public fountain). Estimates of willingness to pay are highly uncertain, as illustrated by the large range of values in the table. Uncertainty arises from methodological differences, but also from the non-linearity and context-specificity of welfare impacts of disruptions, which cannot be captured properly with available data.

Infrastructure services disruptions make firms less productive and competitive

The direct effects of infrastructure disruptions on firms are clear: A firm relying on water to cool a machine must stop production if the access to water is disrupted. A restaurant with an electric stove is unable to operate without power. A firm’s ability to sell or deliver a good is obstructed if the telecommunication network is disrupted or if it cannot access transportation infrastructure. Lack of reliable power, waer, and transport damages the viability of small and micro enterprises ad prevents them from starting up.

In low- and middle-income countries, sales losses due to power outages amounts to $82 billion a year (Rentschler et al. 2019). Disruptions to the water supply infrastructure cost $6 billion annually, and reduced utilization rates of transportation due to disrupted infrastructure cause a loss of $107 billion a year. Yet, these are only the direct costs.

Indirect costs for firms are harder to calculate but must be added to realize the full impact of disrupted infrastructure services. They include effects on long term investments and strategic decisions of firms (Braese, Rentschler, and Hallegatte 2019). Businesses (like households) must often adjust their behavior, e.g., using electricity generators or other alternative energy sources. The cost of electric generators reduces the ability of small firms to innovate and compete by adding unnecessary financial burdens on firms. Furthermore, to cope with unreliable transportation networks, some firms might be forced to increase inventories, thereby increasing storage costs, and further reducing the capital available for innovation. All these added costs reduce the efficiency of capital in an economy.

Table 2: 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 in proximity to, for example, clients or ports	
Telecommunications	• Reduced utilization rates • Sales losses	• Expensive location choices close to fast internet	

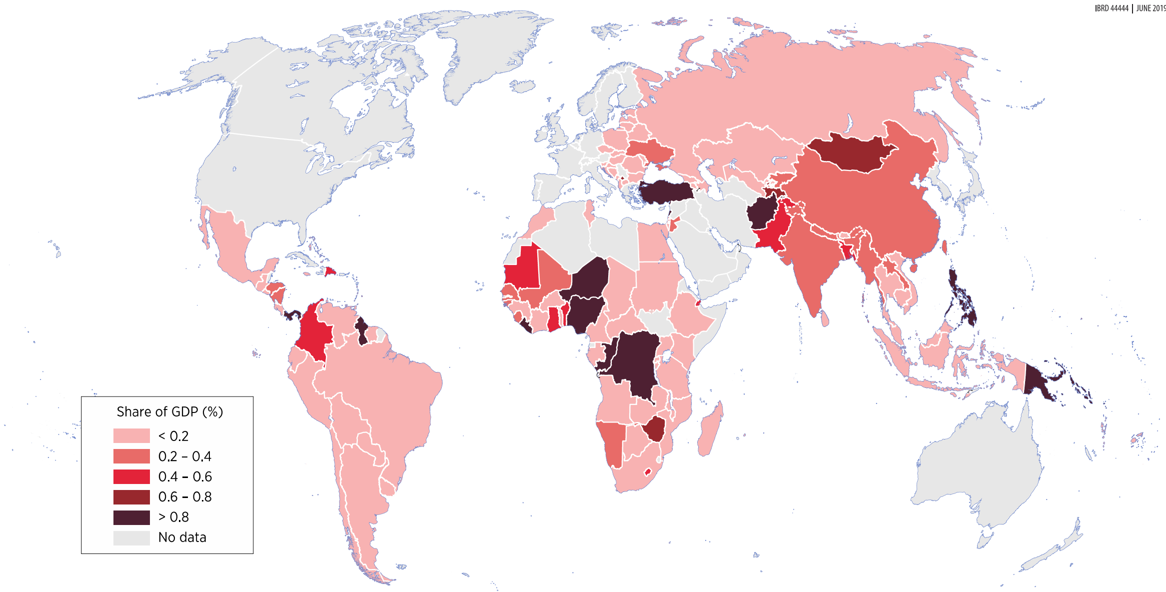
Source: Rentschler et al. 2019.

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

Resilient infrastructure is necessary for economic development. Without resilient infrastructure, businesses face higher barriers to market entry and receive lower rates of investment. Firms in countries with vulnerable infrastructure also show diminishing competitiveness in international markets. In addition to affecting individual firms, direct and indirect effects of infrastructure disruptions also affect an economy's international competitiveness and its ability to generate wealth (Braese, Rentschler, and Hallegatte 2019).

In high-income countries, resilient infrastructure is necessary to stay competitive as a business location. Established business locations lose their competitive edge if they are faced with higher rates of power outages, delays in transportation, and disruptions to their logistical networks.

Figure 2: Additional costs of firms' backup electricity generation as percentage of gross domestic product (GDP), including up-front investments and additional operating costs



Source: Hallegatte, Rentschler, and Rozenberg 2019.

Altogether, infrastructure disruptions caused by natural hazards, poor maintenance, and mismanagement of infrastructure are costing households and firms at least $390 billion a year in low- and middle-income countries. Although this figure is large, it does not cover all the indirect effects that are difficult to measure, such as the longer-term impact on children's education or the lack of diffusion of the best technologies.

Lack of maintenance contributes to a lack of reliability

Inadequate maintenance practices can reduce the ability of infrastructure systems to deliver reliable services—not only during regular times, but especially when hit by natural disasters. In other words, maintenance is crucial for increasing the reliability and resilience of infrastructure systems.

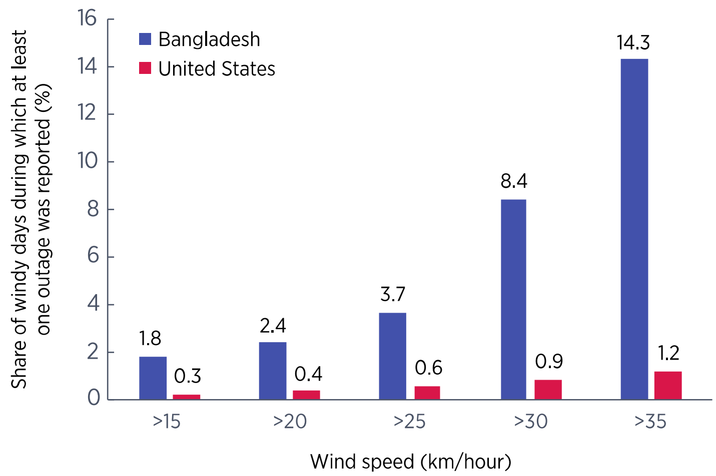
Evidence from the electricity sector illustrates this notion. For electric transmission and distribution lines, vegetation control—in particular the pruning of surrounding trees—is a simple and cost-effective maintenance measure to reduce power outages. Typhoons bring high wind speeds that pose a risk to electricity transmission infrastructure. Poles topple over, or trees are uprooted and fall onto transmission and distribution lines. Evidence from the United States shows that storms are most prone to causing power outages in states that have high forest coverage. For instance, in a state with about 50 percent forest coverage (such as New York), one additional storm is associated with about 463 minutes of additional outage time compared with a non-forested state (Rentschler, Obolensky, and Kornejew 2019). In September 2017, Hurricanes Irma and Maria severely damaged the power grid in Puerto Rico, largely because of trees falling on transmission lines. As a result, 100 percent of Puerto Rico Electric Power Authority customers lost power for more than a week after the storm, and the slow pace of recovery left many customers in the dark for several months (US Department of Energy 2018).

In Vietnam, several coastal provinces with high typhoon exposure have a significant share of their grid located in forested areas. Rentschler et al. (2020) systematically quantify the extent of this threat using satellite imagery and find that overall 36 percent of Vietnam's transmission grid is in forests, and 15 percent is in densely forested areas. With a sizeable portion of the grid located in forested areas, trimming trees near power lines is a necessary and effective measure. Given the current cost of vegetation control practices in Vietnam, the total annual cost of maintaining transmission and distribution lines in forested areas would amount to just $4.1 million to $16.5 million.

Good forest maintenance can also prevent wildfires. Wildfires are a unique vulnerability for transmission and distribution infrastructure. Various case studies illustrate that during high-risk conditions (drought, high temperatures, high winds), curtailments are used to reduce the risk of transmission infrastructure causing a wildfire. The potential risk was illustrated in California in 2007, when San Diego Gas & Electric was found liable for causing three fires that led to three deaths and the destruction of 1,300 homes. The utility ultimately paid out $2 billion in settlements (Daniels 2017). Recent wildfires have put the large utility Pacific Gas and Electric Company under scrutiny due to $10 billion in liabilities from fires in 2017 and unknown amounts from fires in 2018 (McNeely 2018).

When maintenance is neglected, even minor and ongoing pressures can cause disruptions. When vegetation is not controlled, even moderate winds will topple trees and damage transmission lines. In the United States, where maintenance protocols and resources are relatively advanced, the grid demonstrates reliable operations both during low and high wind speed days (Figure 3). Although outages do occur, especially during storms, the levels of disruption are low compared to those in Bangladesh. There, even during low wind speed days, outages significantly exceed those recorded in the United States. Not only is Bangladesh's power system less resilient to major shocks (such as storms), but the system's lack of comprehensive maintenance leads to the grid's lower baseline reliability in the first place.

Figure 3: The vulnerability of the power network to wind in Bangladesh and in the United States



Source: Rentschler et al. 2019.
Note: The bars represent the share of storm days during which at least one outage was reported.

Users of the power grid in Bangladesh are 11 times more likely to experience a blackout than US consumers on a day with average wind speeds above 35 kilometers per hour (kph). In 2013, people in the city of Chittagong, Bangladesh, experienced about 16 power outages due to storms alone. This number corresponds to only 4 percent of all outages in Chittagong, but it "is already more than 15 times higher than the average number of outages experienced by consumers in New York City" (Hallegatte, Rentschler, and Rozenberg 2019).

In water supply networks, lack of maintenance often leads to deterioration of pipes and failure of valves, which in turn leads to leakages in the distribution system, called "nonrevenue water." A 2006 study estimates that every year more than 32 billion cubic meters of treated water physically leak from the world's urban water supply systems, with half of these losses in low- and middle-income countries (Kingdom, Liemberger, and Marin 2006).

In addition, when maintenance is irregular, a water system is less likely to be inspected and thus well known by technicians, increasing the likelihood that illegal connections will go unnoticed and cause commercial losses (water that is treated and delivered to users but not billed). The same study estimates these losses at 16 billion cubic meters a year globally. In low- and middle-income countries, the estimated loss is $5.8 billion a year, of which $2.6 billion is commercial losses. According to Kingdom, Liemberger, and Marin (2006), it is "not unrealistic to expect that the high levels of physical losses could be reduced by half" through improved leak detection, pipe replacement, and maintenance, thereby saving 8 billion cubic meters of treated water a year. Such programs lead to better-quality services, higher utility revenues, and a positive financial flow that enables future investment in rehabilitation and maintenance, which in turn enhances resilience.

Finally, regular cleaning of canals and drainage systems is essential for ensuring the reliability of flood protection systems. In many low- and middle-income countries, the current flood protection systems do not deliver the intended protection, because canals and drainage pipes are clogged by solid waste. Long-term solutions have to include solid waste management, but regular cleaning of canals would also increase the efficiency of the systems.

Although quantification is challenging, similar issues plague other infrastructure sectors. For instance, poor maintenance and cleaning of road culverts or side drains are leading to more significant failures that are expensive to repair. There is also evidence that delayed maintenance leads to roads failing prematurely, causing increased costs.[2] Maintenance interventions invariably give the highest economic returns for investments in the road sector. In hydropower infrastructure, maintenance is not only important for reliable operations, but can also extent significantly the lifetime of expensive assets (Box 1).

Box 1: Preparing operation and maintenance strategies—example for hydropower

With 1,300 gigawatts (GW) of global installed capacity, hydropower accounts for more than 60 percent of renewable energy generation worldwide, and it plays a strategic role in integrating other renewable energies, such as wind and solar. Paying attention to the operation and maintenance (O&M) of hydropower facilities is therefore critical to support decarbonization pathways, to maintain facilities' longevity, and to preserve public safety. Inadequate maintenance may in particular result in major breakdowns and long-term interruptions after 20 to 30 years of service, whereas adequate maintenance could expand the life expectancy of the facilities beyond 100 years.

Investing in O&M for such infrastructure has a high value and return on investment. For example, spending $2 million per year for O&M of a 100-megawatt (MW) hydropower plant can avoid spending $100 million within 15 years' time to replace defective electro-mechanical equipment. Adequate O&M also reduces unplanned outages and associated revenue losses. For example, procurement and replacement of defaulted turbines may result in generation losses of around 440 GWh per year during that period, which would translate into revenues losses over two years in the range of $60 million. All in all, it makes sense to spend $30 million in O&M over 15 years to avoid $160 million losses within the same period, demonstrating the high benefits of adequate maintenance.

In an effort to help enhance the efficiency and reliability of the world's hydropower infrastructure, in 2020 the World Bank published a new handbook on preparing and implementing O&M strategies. These strategies are defined as informed sets of high-level information and decisions towards effective and safe O&M, including (i) a diagnosis, (ii) objectives to be reached, (iii) activities and organizational decisions to reach objectives, and (iv) adequate resources (human, financial, etc.). The handbook was based on case studies in Brazil, Pakistan, Nigeria, Liberia, Uganda, Uruguay, and Argentina.

Source: O&M handbook and related case studies can be downloaded through the following links: https://lnkd.in/ekpaAbd and https://lnkd.in/eX3HzsB.

[2] Orr, David. 2006. *Pavement Maintenance*. Ithaca, NY: Cornell Local Roads Program. https://www.yumpu.com/en/document/read/9021768/pavement-maintenance-cornell-local-roads-program-cornell-/4

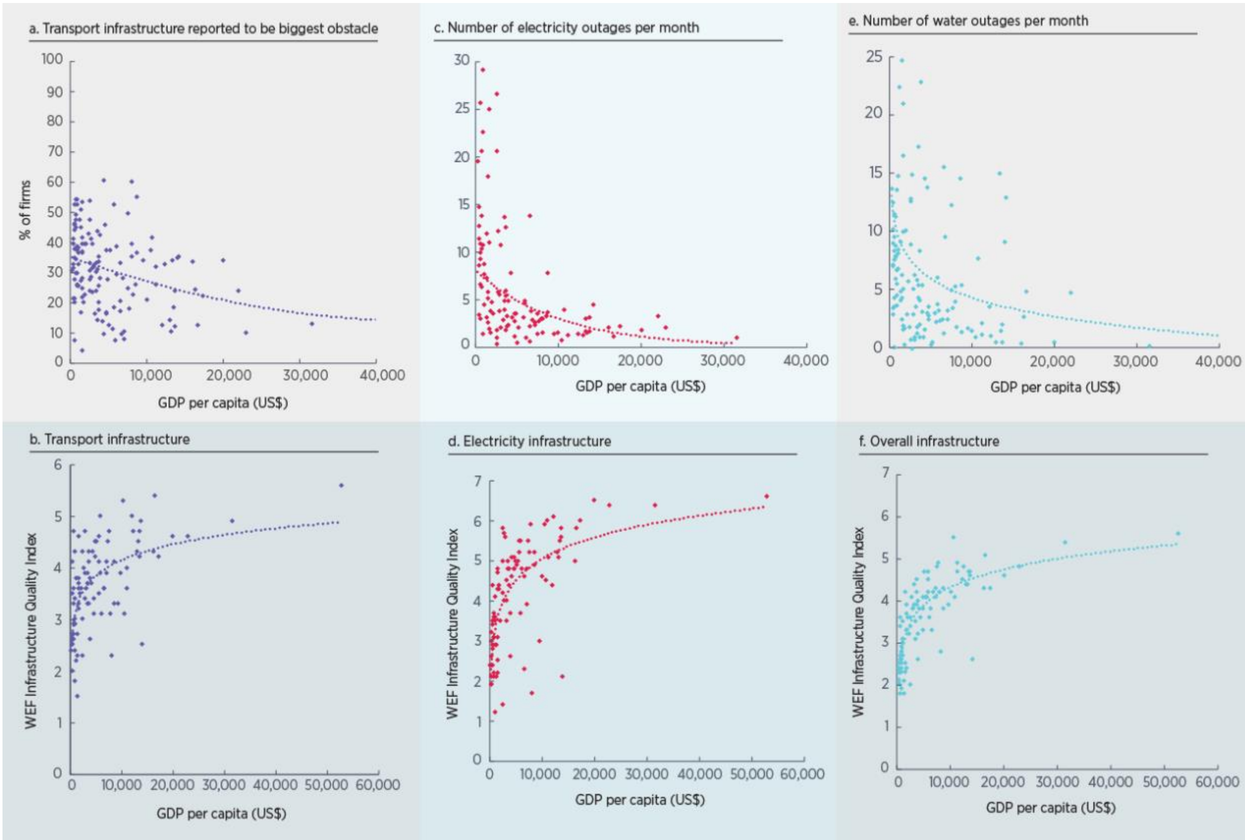
This problem will not fix itself–action is necessary and increasingly urgent

One may argue that infrastructure systems become more resilient with growth, and that their lack of reliability is a problem that will solve itself as countries develop and become richer. However, a set of socioeconomic and environmental trends undermine this idea.

Higher incomes and increased spending alone will not solve the issue

Evidence suggests that poorer countries tend to have lower infrastructure quality and are faced with more disruptions of their power, water, and transport systems (Figure 4). Yet this figure also suggests that the quality of infrastructure does not strictly increase with the income level of a country. There are numerous low- and middle-income countries that outperform richer countries with respect to infrastructure disruptions. In fact, the data suggest significant differences in infrastructure quality for countries at the same income level. The discrepancy between countries is especially apparent at low income levels. Take for example the reliability of electricity in Bhutan (GDP per capita, $2,500), which is comparable to that of many emerging and developed economies, whereas Nigeria (GDP per capita, $2,476) has some of the most frequent power outages of all countries (Kornejew, Hallegatte, Rentschler 2019).

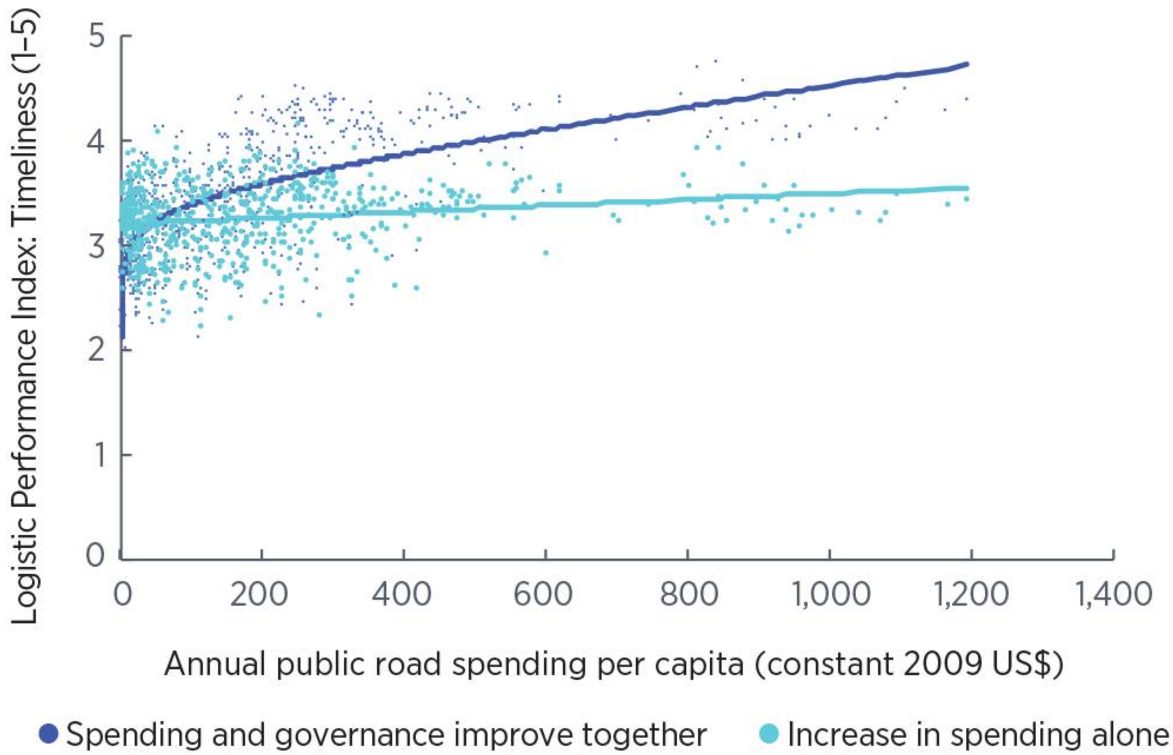
Figure 4: Lower income countries experience lower quality of infrastructure services



Source: Kornejew, Hallegatte, and Rentschler 2019.
Note: One dot per country, using the most recent year for which data are available. The first and the second panel are based on firm-level data (Enterprise Surveys), aggregation to national level using stratification weights. The rightmost panel (Logistics Performance Index: Timeliness) plots a national indicator of transport reliability and thus an inverted measure for transport disruption frequency.

Income levels alone cannot explain the quality of infrastructure, the quality of governance matters. To illustrate this point, Figure 5 shows the relation between transport resilience and per capita road spending, once for the spending alone and once for spending in connection with governance improvements.

Figure 5: Relation between transport resilience and public road spending per capita



Source: Kornejew, Hallegatte, Rentschler 2019.

Empirically, increased government spending on roads increases the quality of transport infrastructure (measured in timeliness) *only if governance is also improved.* Doubling spending on roads increased transport infrastructure performance by roughly 0.27 index points. This would mean increasing the transport service reliability of Mozambique to that of Cambodia. But keeping governance fixed, this improvement is basically nonexistent. The reliability benefit from spending one additional dollar is reduced by a factor of 6 if it is done without progress on governance (Kornejew, Hallegatte, Rentschler 2019). Only 8 percent of variation in transport reliability can be statistically explained with investment spending, contrasted with 44 percent explained by governance quality.

Put differently, improving governance quality may help to reduce spending on infrastructure while maintaining a constant level of service quality and reliability. Improving the quality of governance as effectively as Ecuador did from 2010 to 2013 (+0.23 on the Worldwide Governance Indicators – "Government Effectiveness" Index) could allow an economy to reduce expenditures by 30 percent to 90 percent while maintaining the same level of infrastructure improvement, or enable a large increase in the performance of infrastructure system for the same level of expenditure. The effect of these relative savings, however, are highest for countries with poor governance quality and relatively high levels of per capita spending on infrastructure (Kornejew, Hallegatte, Rentschler 2019).

Economies will be increasingly vulnerable to infrastructure disruption

In parallel, there are strong ongoing trends that magnify the vulnerability of the economy to infrastructure disruptions, making this topic increasingly important for growth and prosperity.

Increasingly complex and efficient supply chains make economies more dependent on infrastructure systems

Modern supply chains are vulnerable to shocks and disruptions of transport systems. The risk of a wide-ranging spread of disruptions along supply chains are a byproduct of the offshoring, outsourcing and just-in-time supply strategies of the past decades. These corporate decisions have led to an unprecedented globalization and complexity of supply chains, resulting in firms becoming more specialized and interdependent (Baldwin and Lopez-Gonzalez 2015). If infrastructure and equipment become too specialized in response to demands for efficiency, their ability to adapt and repurpose in response to crises may be reduced.

Although only a few businesses may experience a shock directly, most can be exposed to the indirect ripple effects, especially when affected firms are upstream ones producing basic commodities. These risks are particularly hard to evaluate because firms often lack a full understanding of their own supply chains and reliance on transport infrastructure. Firms usually know their direct suppliers, but they often struggle to keep track of their sub suppliers, from which about half of supply disruptions seem to originate (Business Continuity Institute 2014). Supply chain managers have to deal with uncertainties, unknowns, and interdependent risks, making decision-making processes particularly complex (Doroudi et al. 2018).

Measures that firms commonly take to reduce costs and increase competitiveness can also aggravate their supply chain risks. For example, reducing inventories and streamlining the supplier base are effective cost-cutting measures that can be adapted to deal with frequent and lower-impact risks. However, firms with low inventories and concentrated suppliers are more exposed to low-probability and high-impact shocks because these strategies reduce flexibility and backup capacity (Stecke and Kumar 2009). Similarly, custom-made supplies may help firms to offer innovative and distinctive products, but they increase the domino effect when a shock hits because they cannot be easily replaced by other suppliers (Barrot and Sauvagnat 2016).

New technologies, digitalization, and decarbonization increase the reliance on electricity

The COVID-19 crisis has shed light on the central role that digital infrastructure and technologies play in our modern societies, and, by accelerating dependence on digital services, it has increased the reliance of the economy on telecommunication and power infrastructure. In the battle against COVID-19, digital technologies are saving lives through digital health, are helping schools provide ongoing learning to their students through remote options, and are helping governments, individuals, and businesses cope with social distancing mandates, ensuring business continuity thanks, for example, to digital payments and remote work.

In the future, these services are bound to be a central part of modern economies, along with increasingly connected cities and transport systems that will include autonomous vehicles. This increased reliance on digital services also increases vulnerability to disruptions in telecommunication or power networks, through natural disasters or human attacks (Zou et al. 2020).

As countries work towards full decarbonization by the second half of the century (in order to meet international commitments to stop climate change), they will rely more and more on electricity. Indeed, decarbonization requires a combination of decarbonization of the electricity system (using renewable energy) while electrifying all energy end-uses (for example, transport and buildings' heat). This electrification process will most likely increase demand for electricity and the share of the economy that depends on power networks. The electrification of transport, in particular, requires paying attention to the resilience of the new connections created between power and transport networks (e.g., electric vehicle charging stations).

Like the rest of the economy, the manufacturing sector is quickly digitizing its production processes and supply chains using cheap sensors and access to telecommunication services. In the near future, whole supply chains could also be disrupted by 3D printing. These new technologies and the "Internet of Things" mean that the manufacturing sector is more and more reliant on telecommunication infrastructure and on power systems to enable storage and transfer of extremely large amounts of data.

Environmental degradation and climate change make infrastructure more vulnerable and more important

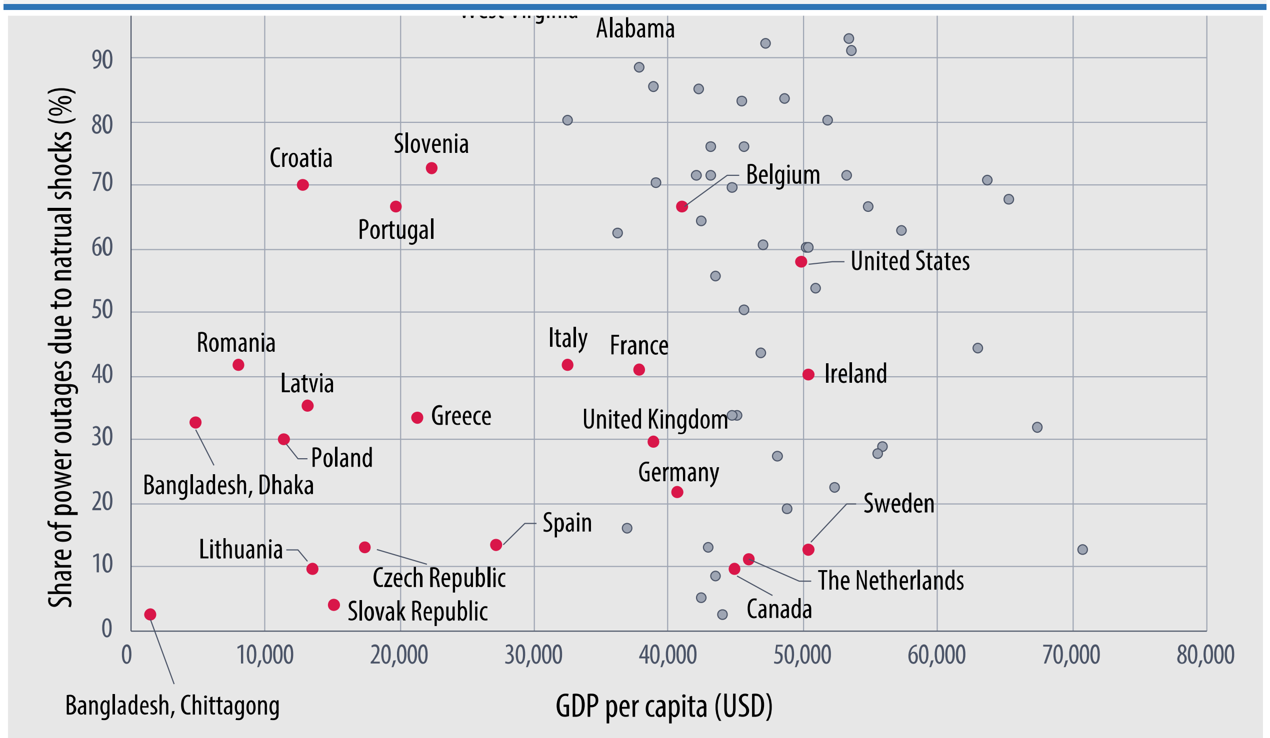
Finally, ensuring the reliability of infrastructure systems is becoming increasingly challenging due to environmental degradation and climate change.

Natural hazards cause significant damage to infrastructure assets everywhere

In low- and middle-income countries, direct damages to power generation and transport infrastructure amount to $18 billion a year. Adding high-income countries bring the total cost to $30 billion per year. But this underestimates the full impacts, which propagate through the consequences of power and water outages, or transport disruptions. Although data tend to be scarce, especially in developing countries, storms, floods, earthquakes, and other natural hazards are responsible for 10 percent to 70 percent of all disruptions, depending on the country and sector.

Figure 6 shows the share of power outages caused by natural shocks and a country's GDP. Surprisingly, the share of power outages caused by natural shocks in many European countries and most of the United States is higher than in, for example, Bangladesh. This indicates that there is no clear connection between the vulnerability towards natural hazards and income levels of a country observable for power grids. This implies that resiliency of infrastructure is not an issue only for developing countries.

Figure 6: Share of power outages caused by natural shocks and GDP



Source: Rentschler et al. 2019.

The total number of outages tends to be larger in developing countries, yet the relative share of outages caused by natural hazards tends to be larger in developed countries (Rentschler et al. 2019). However, this does not necessarily imply that infrastructure networks in developing countries are overall more resilient against natural disasters. Rather, there are more non-natural causes of infrastructure disruptions in poorer countries. But this information does highlight a certain degree of vulnerability that exists even for developed nations. For the time period from 2000 to 2017, 54.8 percent of power outages in the United States and 27 percent in the European Union were caused by natural shocks. In contrast, the numbers for Bangladesh vary from 1 percent to 41 percent, depending on the region.

Furthermore, these numbers underestimate the role of natural hazards both in developing and developed nations because outages caused by natural disasters tend to be longer and affect larger areas than other outages. For instance, in 2007 Bangladesh experienced the largest power outage in its history: All 26 power plants tripped and failed, which led to customers being without electricity for up to one week. And in Europe for the years from 2010 to 2017, outages caused by natural disasters were almost four times as long as other power outages—they lasted 409 minutes on average (Rentschler, Obolensky, and Kornejew 2019).

Effect of climate change on resiliency of infrastructure

Looking at the power grid, several climate change-induced phenomena are likely to increase the risk of outages. More extreme weather patterns mean more droughts, higher temperatures, more storms, and more extreme rainfall. All of this will likely reduce the efficiency of nuclear and thermal power plants. Research suggests that a 1°C increase in average temperature could reduce power output by from 0.45 to 0.8 percent (Mideksa and Kallbekken 2010). A temperature increase will additionally increase stress on the power system because the demand for air conditioning will increase. Droughts and higher temperatures are also likely to affect the current rating of cables and power lines.

In most regions, wind speed is likely to increase with climate change, and atmospheric icing (which negatively affects the performance of wind turbines) is likely to decrease. Climate change will also affect flood frequency, river flows, and evaporation, with implications for dam safety. In addition, climate change will increase temperatures, reducing the efficiency of photovoltaic systems, which could drop by about 0.5 percent for every 1°C of temperature increase (Patt, Pfenninger, and Lilliestam 2013). Another impact of higher temperatures could be increased transmission losses, because of the increased resistance of power lines (Hallegatte, Rentschler, and Rozenberg 2019).

Climate change-induced sea-level rise may require power plant relocation. Sea-level rise will be responsible not only for increased flooding of coastal assets but also, combined with higher wind speeds, for more corrosion of these assets due to saltwater sprays. A study of potential impacts of climate change on the Bangladesh power sector found that around a third of power plants should be relocated by 2030 to avoid inundations caused by sea-level rise (Khan, Alam, and Alam 2013). Another 30 percent of Bangladesh power plants will likely be affected by the increased salinity of cooling water and increased frequency of flooding, while the northern region power plants will probably see a decrease in output because of droughts.

Water systems consist of reservoirs, groundwater pumps, and distribution networks. They provide different services, like bulk water provision, standard water supply and sanitation services, irrigation, and drainage. In addition to supplying water—whether to cities, industry, or farms—water infrastructure is central to reducing natural hazard risks related to floods and droughts. This infrastructure includes multipurpose reservoirs, river embankments, stormwater drains, managed floodplains, and coastal dikes, among others.

Overall, the effects of climate change are likely to increase the need for increased resiliency of infrastructure. The simple fact that infrastructure in low- and middle-income countries is more vulnerable to external shocks and the same nations are also faced with higher exposure towards the effects of climate change makes investments in resiliency that much more important. But also, in high-income countries the need for more resilient infrastructure will increase with an increase in natural shocks on their infrastructure systems.

Other environmental degradation increases the need for hard infrastructure

In many places, reductions in forested areas and wetlands affect the functioning and operational and maintenance cost of manmade infrastructure. Deforestation and the increasing areas of hard landscaping intensity the impact of heavier rainfall. As an example, New York City's water treatment is much simpler than that of other US cities because 90 percent of water is from well-protected wilderness watersheds (National Research Council 2000). Conserving the wetland in Colombo turned out to be a cost-effective measure to reducing flooding within the city, even when accounting for land development constraints (Browder et al. 2019). Both instances show how the integration of nature-based solutions can save money while being sustainable at the same time.

Another illustration is the coral reefs and mangroves that reduce the annual damage from coastal flooding by half (Beck et al. 2018). In Cuba, Indonesia, Malaysia, Mexico, and the Philippines, benefits from coral reefs are largest, with annual savings of more than $400 million per country. Again, the usage of, and thus also the protection of, natural elements, which function as a complement to manmade infrastructure assets, is found to be a cost-efficient solution to increase resiliency.

The solutions: Better assets, better maintenance, better response

What are the necessary steps for ensuring that infrastructure will become more reliable and resilient, without wasting money on unnecessary infrastructure projects? It is essential to consider the three levels to the resiliency of infrastructure:

- the reliability and resilience of infrastructure **assets**,
- the reliability and resilience of infrastructure **services**, and
- the reliability and resilience of infrastructure **users**.

The benefit of higher resilience of infrastructure assets is that it reduces the life-cycle costs, through avoided repairs and reconstruction costs.

Yet infrastructure as we use it does not simply consist of individual assets. Rather we use infrastructure systems that are interconnected networks. The value of each infrastructure asset depends on the reliability and resilience of the whole network. At this level, the benefit of more reliable and resilient infrastructure is that it provides more reliable services at a lower cost.

Yet ultimately what matters is the impact on infrastructure users: households and firms and public services. The impact of infrastructure disruptions can be enormous or negligible, depending on whether the users are able to manage them. At this level, the benefit of more reliable and resilient infrastructure is that it improves productivity and quality of life (Hallegatte, Rentschler, and Rozenberg 2019).

What are the solutions and recommendations to make infrastructure assets, systems, and users more resilient? Here, we highlight a few important opportunities to improve the current situation.

Improve governance quality in investment planning and design

The Quality Infrastructure Investment (QII) Principles, endorsed by the G20 in 2019, are a set of voluntary, non-binding principles. They emphasize that sound infrastructure governance over the life cycle of the project is a key factor to ensure long-term cost effectiveness, accountability, transparency, and integrity of infrastructure investment. The QII Principles also stress the importance of building resilience against natural disasters and other risks, and good governance to ensure a transparent decision-making framework for infrastructure investments, one that considers both O&M and new investments to ensure efficient resource allocation. The QII Principles provide an important set of overarching approaches that countries can use to strengthen infrastructure resilience, including through better maintenance.

Effective governance of infrastructure requires a legal framework and the institutional capacity to plan, assess, prioritize, select, procure, and implement projects. Projects should represent societal value, and should be prioritized, affordable, and delivered efficiently, balancing financial and non-financial considerations. They should also consider their environmental impact, and the implications for overall resilience, and capture opportunities offered by nature-based solution (Box 2).

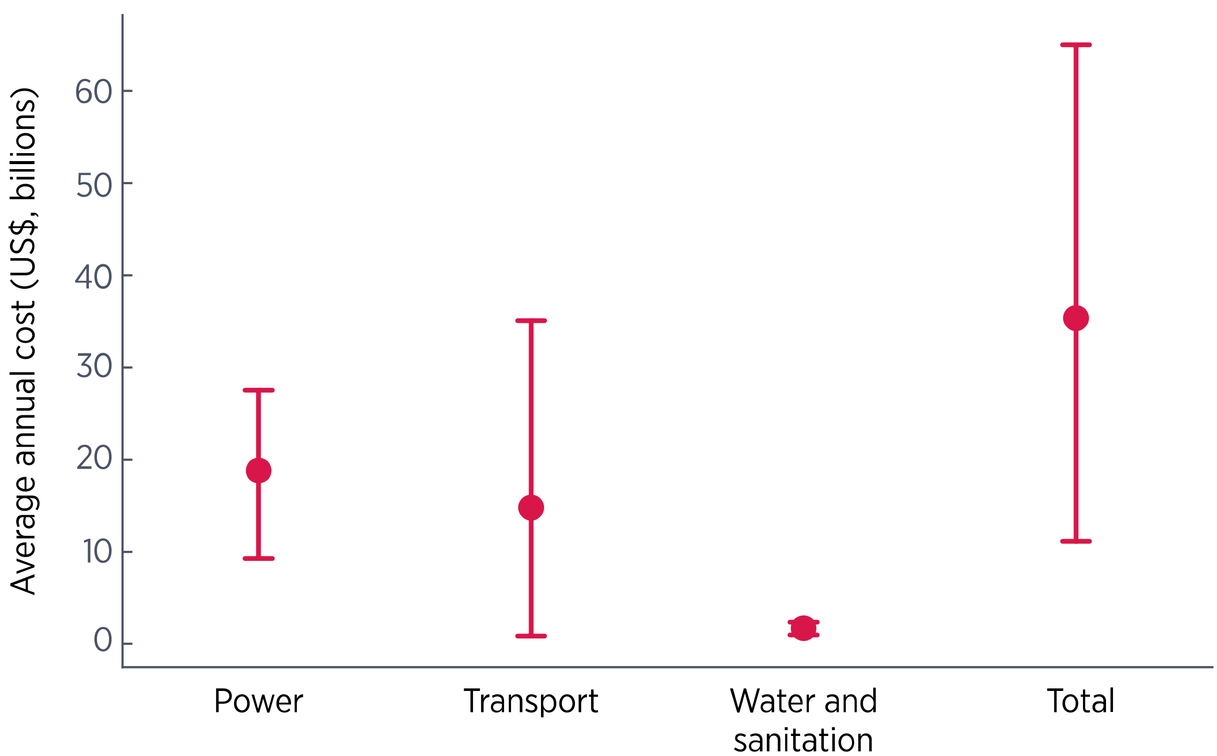
Good governance structures decisions in processes that ensure that the costs and benefits are identified and assessed, and that the appropriateness of the form of project financing can be determined with a set of consistent criteria. Such a system also ensures that political views are included at appropriate points. Good information and thorough project planning and preparation are important in achieving this.

Since a large fraction of infrastructure spending and maintenance occurs at the local level, infrastructure governance needs to include a decentralization component, for instance with a focus on municipal finances.

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. Standards and regulations also 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.

Focusing on low- and middle-income countries, the incremental cost of building up resilience of infrastructure assets is small compared to the benefits, provided the right data, risk models, and decision-making methods are available. Improving the resilience of exactly those assets that are exposed to hazards would increase investment needs in power, water and sanitation, and transport by between $11 billion to $65 billion a year (Figure 7). This range corresponds to only 3 percent of existing infrastructure investment needs and to less than 0.1 percent of the GDP of low- and middle-income countries. Contrasted with the estimated losses infrastructure failures cost these countries—of $380 billion a year—it looks like a very beneficial investment.

Figure 7: 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

What are the returns on investments for making exposed infrastructure more resilient to natural disasters? It is hard to provide an exact estimate because of the layered structure of the returns on investments. One can predict that repairs do not become necessary as often, and that there are fewer disruptions to firms and households. Hallegatte, Rentschler, and Rozenberg (2019) have used a set of 3,000 scenarios to explore the costs and benefits of making infrastructure more resilient.

The analysis shows that, aside from the uncertainty of modelling, investing in higher resiliency of infrastructure is clearly a cost-effective and robust policy choice. In 96 percent of the modeled scenarios, the benefit-to-costs ratio is higher than 1, meaning that for each $1 spent, there is a benefit greater than $1. It is more than 2 in 77 percent of the cases, and higher than 6 in 25 percent (Hallegatte, Rentschler, and Rozenberg 2019). This translates to a net present value of investments in higher resilience of $2 trillion over the life span of new infrastructure assets in 75 percent of the scenarios and $4.2 trillion in 50 percent. Furthermore, the need for investments is only increased through climate change. After accounting for the likely effects of climate change in the scenarios, the median benefit-to-costs ratio is doubled from 2 (without climate change) to 4 with climate change.

Box 2: Well-designed and maintained infrastructure minimizes environmental degradation.

As discussed earlier, environmental degradation contributes to infrastructure disruptions. Soil artificialization and deforestation can for instance increase flood and landslide risks. Accelerated coastal erosion or subsidence threaten many coastal roads and railways, and lead to frequent urban floods. In parallel, poorly designed infrastructure contributes to environmental degradation. For example, erosion control infrastructure in one place can accelerate coastal erosion and flood risks in another. And new roads have been found to accelerate deforestation and biodiversity losses. And poor design and lack of maintenance leads to degraded performance of infrastructure system that lead to increase energy consumption and pollution (e.g., when degraded roads leads to increased congestion, or when poorly maintained power plants have larger emissions). And a longer lifetime of infrastructure assets reduces the need to rebuild for scratch, and thus reduces consumption of construction material (e.g., sand) and energy, and thus carbon emissions.

Nature-based solutions and combination of green and gray infrastructure (e.g., combining mangroves with seawalls to protect a coastline) is an important option to break this vicious cycle. It can also be more cost-efficient than using gray infrastructure alone and prevent further environmental degradation and its consequences. Ideally, the potential from using nature-based solutions and green infrastructure would be assessed early in the planning process and at the system level (e.g., in the water infrastructure masterplan), rather than at the asset level. Successful examples in various sectors, such as water or disaster risk management, are listed in several recent reports, such as Browder et al. (2019) or Ozment et al (2019).

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 (Hallegatte, Rentschler, and Rozenberg 2019).

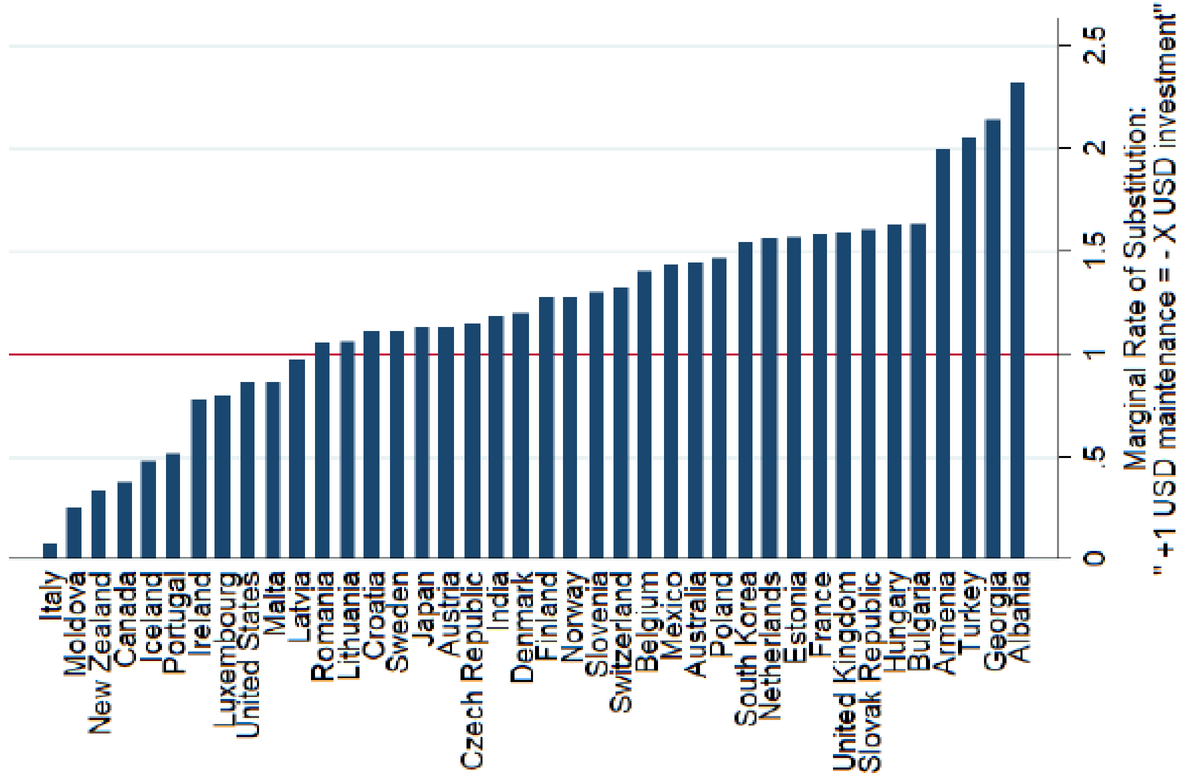
It is also important to note that investments in new infrastructure assets and systems should come with a commitment to maintain them. For instance, the investments necessary to close the infrastructure gap and achieve the Sustainable Development Goals imply significant maintenance funding needs that have to be included in fiscal policy and long-term debt sustainability analyses (Box 2).

Extending asset life by using life-cycle costing, maintenance, operations, and repairs

Improving governance quality or the design of new assets is not the only way to spend more efficiently. Another key factor is maintenance, especially in places with aging infrastructure assets where proper maintenance becomes essential. The evidence suggests that particularly for low-income and lower middle-income countries, approaches towards asset management are of weaker quality than for other parts of the project cycle (World Bank 2020).

Often the trade-off between maintenance and investment is more favorable towards maintenance. As seen in Figure 8, for most countries the returns are higher if they spend money on infrastructure maintenance rather than on building new assets. It shows how much investment could be saved relative to a marginal increase in maintenance spending, while leaving overall infrastructure quality unchanged.

Figure 8: Trade-offs between building and maintaining public roads.



Source: Kornejew, Hallegatte, Rentschler 2019.

Note: Marginal rate of substitution between public road maintenance and investment spending. The red line marks the 1:1 ratio, e.g., economies above could save road investment coasts by shifting funds towards maintenance (based on OECD road spending data).

Box 3: An increase in maintenance spending is critical to close the infrastructure gap

Rozenberg and Fay (2019) use a systematic approach to estimate the funding needs (capital and operations and maintenance) for closing the service gap in water and sanitation, transportation, electricity, irrigation, and flood protection by 2030. (Telecommunications is not included in their analysis because it is mostly privately funded.) They estimate that new infrastructure could cost low- and middle-income countries from 2 percent to 8 percent of their GDP a year to 2030, depending on the quality and quantity of infrastructure services sought and the spending efficiency achieved to reach this goal (Table B2.1). Moreover, with the right policies, investments of 4.5 percent of GDP could enable low- and middle-income countries to achieve the infrastructure-related Sustainable Development Goals and stay on track to full decarbonization by the second half of the century.

Infrastructure spending on capital and maintenance needs in low- and middle-income countries between 2015 and 2030, by sector

	% of GDP		$, billions	
Sector	Capital	Maintenance	Capital	Maintenance
Electricity	2.2	0.6	780	210
Transport	1.3	1.3	420	460
Water and sanitation	0.55	0.2	200	70
Flood protection	0.32	0.07	100	20
Irrigation	0.13	—	50	—
Total	4.5	1.99	1,550	760

Source: Rozenberg and Fay 2019.

Note: — = maintenance costs of irrigation infrastructure are included in the capital costs.

The ambitious goals and high efficiency of Rozenberg and Fay's "preferred scenario" depend on smart policies and good planning. Countries would take long-term climate goals into account now to avoid expensive stranded assets later; they would invest now in renewable energy; they would combine transport planning with land use planning, resulting in denser cities and cheaper and more reliable public transport; and they would develop reliable railway systems that freight haulers would find attractive. Decentralized technologies, such as mini-grids for electricity and water purification systems powered by renewable energy, would be deployed in rural areas.

However, maintenance plays a key role, and improving services requires much more than capital expenditures. Success will depend on ensuring a steady flow of resources for operations and maintenance. In the preferred scenario, low- and middle-income countries would need to spend 2.7 percent of GDP a year to maintain their existing and new infrastructure, in addition to the 4.5 percent of GDP in new capital (Table B2.1). Meanwhile, good maintenance generates substantial savings, reducing the total life-cycle cost of transport and water and sanitation infrastructure by more than 50 percent.

Funding of maintenance is often challenging. Underinvestment in operation and maintenance is common because it is generally easier to raise resources to finance new investment or major rehabilitation than to cover continuous operation and maintenance costs. Maintenance is also less visible than new investments and can usually be delayed, which makes it an easy target for budget cuts (Briceno, Estache, and Shafik 2004; Regan 1989). Appropriate and reliable budgetary allocations—or use of contracts that effectively precommit adequate maintenance expenditures such as public-private partnerships and performance-based contracts—are necessary to ensure that good maintenance can actually happen.

Improving maintenance and operation is a no-regret option for boosting the resilience of infrastructure assets while reducing overall costs. Rozenberg and Fay (2019) find that, without good maintenance, infrastructure capital costs could increase 50 percent in the transport sector and more than 60 percent in the water sector. An analysis of member countries of the Organisation for Economic Co-operation and Development (OECD) suggests that every additional $1 spent on road maintenance saves on average $1.50 in new investments, making better maintenance a very cost-effective option (Rentschler et al. 2019).

There is indeed strong evidence that good maintenance increases the lifetime of assets. In Salzburg, Austria, most water pipelines are more than 100 years old, but they suffer very low water losses because of an effective strategic maintenance plan (European Union 2015). Fukuoka City, in Japan, shows how additional investment can delay the need for asset replacement and lead to a more resilient water supply system (Box 3).

In addition, maintenance is critical for ensuring that assets can withstand extreme events. World Bank (2017) argues that better asset management systems and better maintenance should be the top priority for small island developing states in order to increase the resilience of their transport systems. For example, the report finds that improved road maintenance could reduce asset losses by 12 percent in Belize and 18 percent in Tonga.

Approaches to improve maintenance and operations, including private sector contracting

How can proper maintenance be ensured? An important tool is the infrastructure asset management system, which utilities can use to better manage their operations. Such a system includes an inventory of all assets and their condition, as well as all the strategic, financial, and technical aspects of the management of infrastructure assets across their life cycle. The objective is to move toward an evidence-based preventive maintenance schedule and to move away from a reactive approach to maintenance. A combination of *routine* maintenance (e.g., annual frequency) with *periodic* maintenance (e.g., every 5 years) will allow for an extended lifetime of an infrastructure, but also a better and more constant performance level over time.

A simple infrastructure asset management system focuses on each asset, independent of the system in which it functions. The system includes how much assets cost, who is responsible for maintaining them, their condition and functionality, assessment of potential maintenance intervention scenarios, and when they require rehabilitation. A more complex asset management system includes photographs and plans of all assets, their component parts, their maintenance schedules, and details of all actions involving the asset since it was designed. It includes an estimate of the life-cycle costs of the asset, the actual depreciation each year, amortization details, and possible development to better align the current components with the changing needs of users and their clients. New technologies – including remote sensing, drones, imaging, and digital technologies – offer opportunities to collect and maintain data on the condition of infrastructure assets at a low cost and can facilitate preventive maintenance (see next section below).

Box4: Fukuoka City, Japan—a life-cycle cost approach to extending asset life for a resilient water supply system

In 1978, Fukuoka City suffered from a severe drought. Rainfall was half the annual average and the city had to suspend normal water supply for 287 consecutive days and, on average, citizens had access to water supply for only 10 hours per day. To provide a more resilient water supply, the city undertook multiple investments to reduce operating expenditures and delay future capital expenditures in the water sector. The city revised its procurement policy to require polyethylene sleeves covering all new distribution pipes. The sleeves extend the pipes' lifespan by 40 years with an additional cost of 1 percent to 2 percent. This decision led to an approximately 13 percent reduction in the net present value of pipe replacement costs. Furthermore, the city established a Water Distribution Control Center to prevent pipe damage and leaks by reducing pipe pressures. As a result of these efforts, Fukuoka City reduced the water leakage rate from 14 percent in 1979 to 2 percent by the mid-2000s. Fukuoka City also introduced complementary interventions to control water demand, including usage-based tariffs and a public awareness campaign, which delayed future capital expenditures by suppressing the increase in water demand.

Life-cycle costing was the underlying principle in Fukuoka City's efforts to become a water-conscious city. The policy objective was to make full use of existing scarce water resources through efficient water management and demand control. This objective was achieved by making up-front additional investments in infrastructure to reduce operating expenditures, extend asset life, and delay future capital expenditures.

Fukuoka City. 2009. "Records of the Droughts in 1978 and 1994." April 1. https://www.city.fukuoka.lg.jp/mizu/somu/0053.html.

A complex asset management system also documents the functional context in which the infrastructure delivers its services. It identifies the related infrastructure systems that affect its ability to deliver the services required, the contact people, and the details of collaborative maintenance. Whatever form it takes, effective asset management relies on stakeholder commitment, effective institutions, and adequate resources. Several countries are pursuing this objective through road tariffs, with the proceeds being deposited in a special account or *road fund* to be managed by an independent board, with private participation. Road funds establish a reliable and well-managed source of finance to address the issue of building institutional and financial capacity for maintenance of the road network. Revenues for the road fund can come from a road tariff including a fuel levy, vehicle license fees and international transit fees (Gwilliam, Ken.2011).

One solution that is widely used for the maintenance of transport infrastructure, especially roads, is performance-based contracts (PBCs) (Iimi and Gericke 2017; Lancelot 2010). These contracts explicitly link payment of contractors to the performance of assets, providing a powerful incentive for the contractors maintaining or operating an asset to ensure that its reliability is accounted for in all decisions (box 4). However, designing and implementing PBCs requires capacity on behalf of both the government and contractor, and allocating too much risk to the contractor can have significant impacts on costs, or place the PBC at risk of failure (Henning, Hughes, and Faiz 2018).

Box 5: Using performance-based contracting (PBC) to reduce water leakage in Vietnam

In 2005, Vietnam's largest city, Ho Chi Minh City (HCMC), did not have enough water supply to meet demand. More than 40 percent of the water produced was lost as leakage. Supply was intermittent. To increase supply to customers, the state-owned water utility, Saigon Water Corporation (SAWACO), competitively procured a contractor to enter a performance-based contract (PBC) for non-revenue water (NRW) reduction, with a focus on leakage reduction in one of its six hydraulic zones. In a different zone, SAWACO implemented a traditional approach for leakage reduction, with remuneration based on inputs instead of outputs. SAWACO chose to implement both approaches at the same time to learn the strengths and weaknesses of each approach. Some of the results achieved were as follows:

- Saved 122 MLD (million liters per day) of water after six years, improving reliability of supply and allowing new customers to be connected
- Established 119 District Metered Areas (DMAs)
- Saved about $100 million worth of capital expenditure on alternative water supply sources (using typical benchmark costs, a new supply of 122 MLD could have cost around $120 million, compared to the NRW-PBC cost of $15 million)
- Repaired more than 15,000 leaks
- Reduced operating costs (energy and chemical costs) per unit of water sold because a higher percentage of water produced was sold
- Reduced leakage faster than the traditional project, which was developed at the same time as the PBC

Source: World Bank Case Study on the Performance-Based Contract in Ho Chi Minh City, PPIAF.org.

Can the private sector play a role? Maintenance and asset management can be improved through contracting with the private sector and public-private partnerships (PPPs) or concessions, as well as performance-based contracting, which provides accountability around maintaining infrastructure assets in good condition throughout the life of the concession or contract. As mentioned above, a performance-based contract is a project delivery method based on the principle of "what" is required, not "how" to achieve it. It is an output-based contract that sets the performance expected from the final output. A service-level agreement (SLA) and key performance indicators (KPIs) are established to measure the performance standard of the output. The SLA and KPIs should be clear and measurable because the payment is based on the output. The full payment is made only if the output meets the agreed standard. SLA and KPIs measure the standard of the output. KPIs can be built into the PPP contract so that the performance is linked to actual delivery by the private concessionaire. Global Infrastructure Facility is supporting the government of Ukraine in its road asset management by involving the private sector (Box 5).

Box 6: Global Infrastructure Facility support to Ukraine's road asset management program and the role of the private sector

Road infrastructure is the backbone of Ukraine's transport ecosystem, handling 37 percent of the country's international trade value; however, 90 percent of its extensive road network is in poor condition and in need of current and capital repairs. Ukraine has dedicated $200 million per year on average to road repair and maintenance in the last decade, but to fund the repairs of its core network of approximately 23,000 kilometers (km) the country would need an estimated $6.8 billion of investment over the next three to five years.

To achieve the sustainable delivery of resilient quality roads to its users, the Global Infrastructure Facility (GIF) in partnership with the World Bank and International Finance Corporation (IFC) is supporting the Ukraine's Ministry of Infrastructure (MIU) and the national road agency Ukravtodor to: i) the develop a road asset management model under a program to rehabilitate, upgrade, and maintain Ukraine's core road network; and ii) identify a pipeline of pilot projects at the pre-feasibility stage to be structured under the program. The program's business model is centered on the existing Road Fund and suggests an availability payment-based PPP solution to engage the private sector and facilitate quality road network upgrades and long-term maintenance through private investment. The program is expected to include performance-based availability (or maintenance) mechanisms and safety performance payments to incentivize maintenance of the road and encourage the operator to meet service level agreements.

In October 2020, the MIU and Ukravtodor presented Ukraine's "Road PPP Program: Partnering for Better Roads,"across a three-phased program, supporting the economic development of Ukraine through high-quality and safe highways. The program's concept originated from the recommendations of GIF's Project Readiness Assessment (PRA) of the L'viv-Krakovets Highway to adopt a network-wide approach with brownfield solutions to attract private investment for the upgrade and maintenance of the existing network. The PRA showed that construction costs of €250 million would require a subsidy of €330 million if the highway were procured as a greenfield toll-based PPP and would be unattractive to private investors due to high costs and low traffic levels. A program of brownfield updates would represent a more sustainable and bankable solution to deliver an adequate road network by maximizing economic benefits and minimizing costs to Ukraine's economy. GIF is continuing to work with the IFC and the World Bank to support MIU and Ukravtodor with the structuring of the first pilot transactions under the program and to ensure the long-term sustainability of the program.

Source: World Bank. 2018. "Strategy for Prioritization of Investments, Funding and Modernization of Ukraine's Road Sector" Report No: AUS0000345, June 2018 and Global Infrastructure Facility 2021.

Even with preventive maintenance, the capacity to respond quickly to incidents and to dispatch teams and resources to repair damaged or failing assets is critical for a reliable infrastructure system: such emergency response services can easily be included in concession or performance-based contracts. Utilities and agencies need information-gathering systems and contingency plans, clear attribution of responsibility in case of incidents, and an appropriate stock of parts and emergency equipment. Countries that are unable to respond quickly to isolated system failures are obviously unable to deal with natural disasters, where the spatial scale of the damages is usually much larger.

And when disasters cause large-scale damage (and reconstruction needs), an integrated strategy including disaster risk finance and implementation plans (e.g., with pre-approved contracts for debris removal and basic infrastructure reconstruction) can greatly accelerate recovery (Hallegatte and Rentschler 2018). World Bank (2021) proposes an operational framework for financial protection of critical infrastructure combine three interconnected parts:

1. **Financial protection of physical assets.** This protection means having finance and plans in place to rehabilitate or reconstruct critical assets after a disaster. Protection could include, for example, public assets insurance or budgetary mechanisms such as disaster funds.
2. **Shock-responsive systems that link financial and operational preparedness to ensure rapid recovery of critical services.** Such preparedness means having plans, finance, and systems in place to rapidly mobilize action in the event of a shock, thereby either ensuring continuity or reducing the severity and duration of any disruptions to critical services.
3. **A national financial protection strategy that integrates critical infrastructure to efficiently manage the contingent liabilities related to such shock-responsive systems**. Here the focus is on (a) reducing any financial shock to government balance sheets that might arise from the costs of recovering and reinstating critical services postdisasters and (b) ensuring that timely, predictable, and cost-effective finance is available in emergencies so the government can quickly restore services when needed.

Using new technologies to improve efficiency of existing infrastructure

Infrastructure technology, or InfraTech, can be described as the integration of material, machine, and digital technologies across the infrastructure life cycle. By its broadest definition, InfraTech can be considered any technology that impacts the development, delivery, and ongoing operation of infrastructure. This may include technologies used to define the strategic requirements of infrastructure or enable data-driven decision-making, innovations in finance and funding that support the commercial management of an asset, or technologies integral to the relationship a customer has with infrastructure services. From a policy perspective, it is important to make the distinction between the design of technologies in the operations of infrastructure planning and delivery versus the integration of technologies into the structures themselves, which changes the nature of infrastructure assets from simple inanimate objects to dynamic information systems. Given the importance of the Infratech, G20 endorsed the 'Riyadh InfraTech Agenda' in 2020 (see box below). There are several benefits to using Infratech:

- First, InfraTech improves efficiency and reduces costs through better data management and flow of information. The traditional approach looks at each input and output in isolation. InfraTech can connect multi-sourced data, leading to cost savings across the life cycle of the asset. This approach can support governments in better planning, decision-making and implementing just-in-time solutions.

- Second, InfraTech can enhance economic, social, and environmental aspects by providing a cross-sectoral view. For example, there may be similar issues affecting local communities across various projects, which are most likely run by more than one government agency. By collecting the information using technology across the board, service providers can target specific areas of improvement to enhance social and environmental outcomes, instead of using a project-by-project approach.

Box 7: G20 Riyadh InfraTech Agenda

Infrastructure Working Group under G20 endorsed the Riyadh InfraTech Agenda. The focus was to highlight the important role technology can play in helping countries make well-informed decisions and achieve more efficient financial outlays, by mobilizing private sector investment, by enhancing service delivery and by achieving environmental, social, and economic benefits. The Riyadh InfraTech Agenda provides high-level policy guidance for national authorities and the international community, including MDBs and IOs, to advance the adoption of new and existing technologies in infrastructure. The Agenda aims to harness technology to deliver quality infrastructure investment; promote inclusive, accessible, sustainable, and affordable infrastructure in view of lifecycle costs; mobilize private-sector financing; and support the development of infrastructure as an asset class. This guidance includes a set of voluntary, non-binding elements.

Riyadh InfraTech Agenda includes six elements which are as follows:

1. Leverage InfraTech to enhance economic efficiencies and mobilize private sector investment to promote growth and sustainability
2. Promote technologies that foster inclusivity, sustainability, resilience, and good governance
3. Accelerate innovation and economic dynamism in InfraTech related industries to support economic recovery and growth

4. Foster a robust data ecosystem to improve resilience and better inform infrastructure planning, operation, maintenance, and investment decisions
5. Develop agile and flexible policy tools that promote potential growth, productivity and innovation while mitigating risks
6. Promote national and international cooperation in R&D and knowledge sharing

Source : 2020 Global Infrastructure Hub

What synergies and trade-offs are there in a post-COVID recovery phase?

The COVID-19 pandemic has caused an unprecedented worldwide crisis. Devastating economic impacts have been felt across the spectrum, from multinational companies through small and micro enterprises to daily paid, migrant, and informal workers and their families. Lockdowns have led to the disappearance of many workers' disposable income, many businesses' customers, and, in numerous locations, the closure of the business activities of all but the most essential services.

Potential job creation from infrastructure construction and maintenance[3]

The impacts of the crisis have disproportionately affected low-paid and informal workers, who have been laid-off in many industries like food, tourism, transportation, retail, or entertainment. Employers have not been able to continue paying salaries given the widespread disappearance of income, notwithstanding their legal obligations and the support programs introduced by some governments. Migrant workers have not only lost their sources of income, but have had to travel

[3] Adapted from "Response to Covid-19 - Employment Creation through Infrastructure Investment," James Markland.

hundreds of kilometers without support to reach their homes, and are finally forced to contemplate rebuilding lives in their home communities, often while facing quarantine restrictions or discrimination. The informal sector has been hit by the lack of customers brought about by the lockdowns and the drop in disposable incomes of their customers.

Once the health crisis is under control, governments will need to generate meaningful employment to provide income for those who have lost their jobs. A clear understanding of the available approaches and their associated roll-out strategies is critical in view of the uncertainties surrounding the start and pace of the recovery phase, the period over which COVID-19 will continue to be a challenge, and employment creation needs. This section focuses on the options for the creation of infrastructure-related employment.

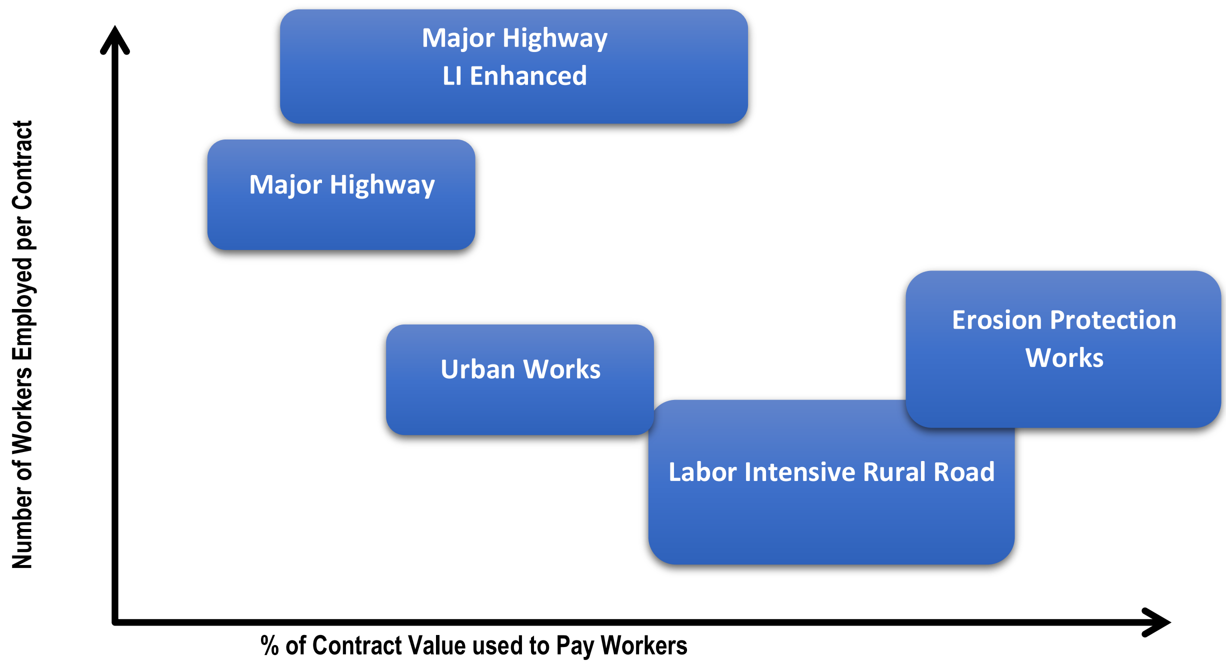
To be effective and sustainable, programs must match needs with opportunities. Factors that influence solution choice include the attitudes of stakeholders, availability of skills, and local infrastructure needs. It is easier to scale up and adjust existing activities than start new ones, especially for cross-sectoral programs that are more flexible in adapting to diverse opportunities and bring other advantages. Although the discussion and examples that follow focus on the road sector, there are many opportunities in other sectors that should be considered.

Any form of infrastructure investment can generate employment through construction activity, which allows governments to directly stimulate economies. Infrastructure investment has been traditionally used by governments to recover from economic recessions, for example in the United States during the Great Depression. There is also an economic “trickle down” effect from construction work: Local businesses and informal vendors will benefit from large projects by supplying raw materials, transport, accommodation, food, and other goods and services.

Any infrastructure over 150 years old was built using labor-intensive methods. Roads (and other infrastructure) built by hand are often more resilient than those constructed by machines due to the greater attention to detail that is possible during the construction process. But as construction techniques have evolved, many of the tasks once performed by manual labor have been taken over by machines, reducing the number of workers required on a construction site, and the proportion of a contract’s value that is used to pay wages. This change has not been uniform, and substantial numbers of workers continue to be used in some types of construction. Although most roads, from major highways to minor access roads, are now constructed using a great deal of machinery, there are situations where simple paved or unpaved rural access roads implemented at the state or district levels can be constructed using methods that require numerous workers.

In considering employment creation programs, it is important to appreciate the difference between the number of workers that are employed on a specific contract or activity and the proportion of that contract value that is used to employ workers. This distinction is illustrated in Figure 9. For example, although labor-intensive erosion protection works convert a high proportion of the investment value or contract cost into jobs, a larger number of workers may be employed on a major highway contract, even though a smaller proportion of that investment is spent on wages. The key indicator to use in assessing the effectiveness of an activity in converting investment value into employment is the number of jobs created per unit of cost.

Figure 9: Employment creation for different types of work



The key to success is to maximize the amount of employment for a given level of investment while retaining a reasonable degree of efficiency and ensuring quality of the end-products. The adoption of labor-intensive construction methods requires a conscious decision to identify and prioritize those types of activity that can be undertaken with a high proportion of manual labor. Whatever the level of employment created, there will always be a need for some level of other inputs, whether in the form of transport, construction materials, machinery, or hand tools.

The opportunity to boost maintenance through public works programs

Labor-based public works and services provide an important policy tool to governments in developing countries for addressing unemployment and poverty. Investments in public works and services can generate significant amounts of employment, specifically recurrent infrastructure construction or maintenance activities. Such labor-based programs have historically been used in countries where unemployment and/or underemployment are high, and at times of macroeconomic or climate shocks, or after natural disasters and conflict, and are applied in both rural and urban contexts. For example: (i) in Indonesia, the government launched the Social Safety Net Program in 1998-99 in response to the financial crisis; (ii) in India, the State of Maharashtra launched an Employment Guarantee Scheme in the face of an acute drought in 1972-73, and in 2005 the government enacted the National Rural Employment Guarantee Act, which provides guaranteed employment in public works, including road construction and maintenance; and (iii) in South Africa, where the causes of unemployment are structural and historic, the government launched the Expanded Public Works Program in 2004, which was aimed at developing the skills of the unemployed, and providing essential social services and physical infrastructure to disadvantaged communities. South Asia spends 26 percent of its Social Safety Net budget on public works and services programs, and in Europe and Central Asia it is 36 percent.

A recent study[4] of the employment-generating potential of road contracts in Lebanon and Jordan gives an indication of the amount of employment that can be created (Table 3). Most of the contracts were mechanized, and it was found that approximately 4,200 person-days of employment per kilometer could be created through rural road construction and significantly more, 8,000 person-days per kilometer, on urban roads.

Road maintenance work shows a significantly higher conversion of cost into salaries at approximately 50 percent, significantly more than for mechanized road construction works, where the proportion is unlikely to exceed 25 percent. These results confirm the intuitive expectation that most mechanized construction work will convert a small proportion of the investment into employment opportunities. The Feeder Road program in Mozambique reopened 6,000 kilometers of unpaved rural road over a 13-year period after the civil war. Provision of employment was an important tool to increase social stability in a society recovering from conflict. Although labor-intensive programs can be effective in creating high levels of employment for a given level of investment, the programs need to be exceptionally large in scale to generate the levels of employment needed to assist recovery now. Maintenance and labor-intensive construction generate a high level of employment in relation to the investment: These areas should therefore be the focus for maximizing long-term job creation.

Table 3: Employment generation on sample road contracts in Lebanon and Jordan

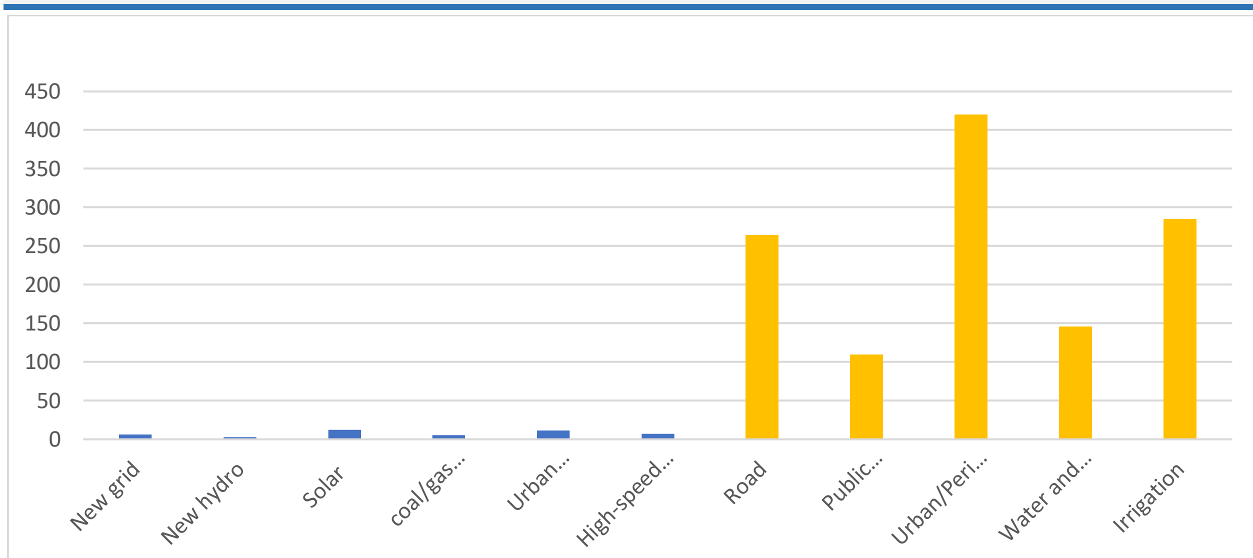
Item	Road #1	Road #2	Road #3	Road #4	Road #5	Road #6	Road #7	Road #8	Road #9
Road length (km)	**1.7**	**14.7**	**12.0**	**4.3**	**7.3**	**47.3**	**22**	**na**	**na**
Road type	**Urban hwy**	**Rural hwy**	**Rural hwy**	**Rural**	**Urban hwy**	**Rural hwy**	**Rural**	**Rural**	**Rural**
Construction type * Mech/ LI/ maint	**Mech**	**Mech**	**Mech**	**LI**	**Mech**	**Mech**	**Mech**	**Maint**	**Maint**
Employment per kilometer (person-days/km)	**7,933**	**4,219**	**4,050**	**1,849**	**8,190**	**na**	**na**	**na**	**na**
Employment created per cost	**4,381**	**4,183**	**6,446**	**21,525**	**8,168**	**na**	**na**	**na**	**na**

[4] World Bank and the International Labour Organisation. *Assessment of Infrastructure Investments in Transport and Job Creation: Examples from Road Sector Investments in Lebanon and Jordan*. 2018.

Item	Road #1	Road #2	Road #3	Road #4	Road #5	Road #6	Road #7	Road #8	Road #9
(person-days / $1 million)									
Proportion of cost spent on wages	**18%**	**17%**	**22%**	**69%**	**33%**	**22%**	**33%**	**51%**	**50%**
* Construction types: Mech = Mechanized with heavy equipment; LI = Labor intensive, high proportion of labor and some light equipment; Maint = Road maintenance activities.									

In the aftermath of the COVID-19 crisis, several countries indicated they will want to create short-term employment for many people, especially those most affected by the pandemic. The World Bank Transport Team in Pakistan reviewed the employment potentials of several public works activities using data from various projects around the world. It estimated the employment content (percentage of contract value that goes to wages and person-days of work generated) for about 30 labor-based public works activities in the roads, public building, urban and peri-urban, water and sanitation, and irrigation sectors to look at their potential for job creation. As shown in Figure 10, the number of days or years of work created by some of these activities can exceed 250 per $1 million of spending, suggesting that labor-based maintenance creates a much larger number of days of work than the construction of new infrastructure assets, which can employ a larger number of people but over a shorter period.[5]

Figure 10: Jobs created (in person-year) by $1 million in public spending, for new infrastructure assets (blue) and maintenance (yellow)



Source: World Bank estimates, based on International Energy Agency (2020) and review of maintenance contracts in Pakistan.

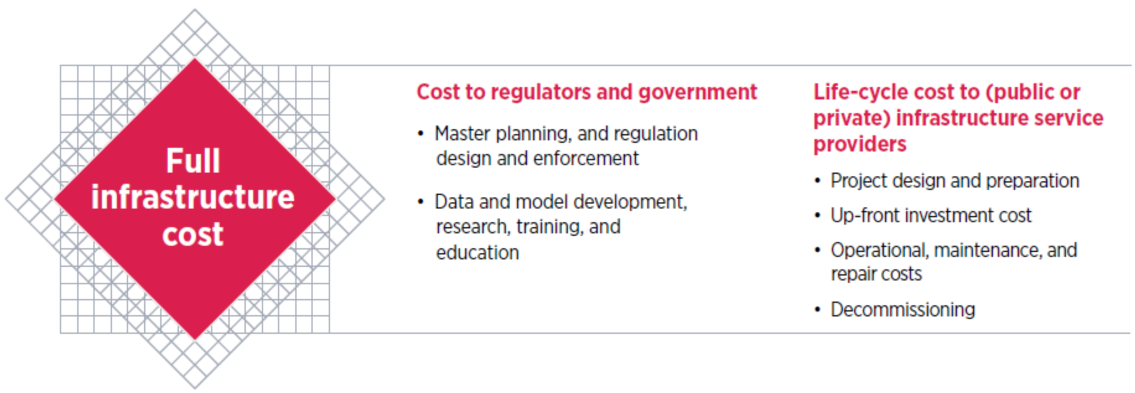
[5] However, many of these jobs are part time.

The effect of financial constraints on resilience and technology decisions

COVID-19 has magnified an increase in sovereign debt that was already worrisome before the crisis. With the cost of the crisis—both in terms of lost revenues and additional spending—debt levels will reach unprecedented levels, threatening the access of many countries to additional borrowing.

Such financial constraints can push countries toward solutions that have lower up-front costs because of lower resilience or higher operational costs, even if these options have higher life-cycle costs or major social costs. Countries with fragile infrastructure systems often spend large amounts to repair and maintain this infrastructure, compounding the challenge of limited fiscal space to finance an investment that could improve reliability and reduce vulnerability. Escaping this vicious circle of high fragility, high maintenance, and low investment requires a temporary increase in spending, which may be difficult to access in the next decade.

Figure 11: High-quality infrastructure requires providing for multiple funding needs



Governments in low-, middle-, and high-income countries already struggle to finance the infrastructure investment needed to meet demand (Rozenberg and Fay 2019c). Many infrastructure systems struggle to meet normal demand, with inadequate power generation capacity, unreliable internet services, or highly congested public transit and urban roads, even in normal times. Systems that cannot satisfy normal demand are naturally highly vulnerable to any shock that reduces supply—for instance, the failure of one power plant or transmission line or the closure of a road. And with increasing needs in social sectors—especially education and health—the pressure to reduce investments in infrastructure may well increase, exactly when the needs in this sector remain extremely high.

Conclusion

Spending better means spending smarter. It is important to consider where each dollar spent on infrastructure is used best and to create the means and support necessary to make such decisions. This means looking at the allocation of expenditure between infrastructure maintenance and new projects, increasing spending efficiency and improving governance quality. It also means collecting essential data and focusing on a clear and precise planning phase that looks not only at hard infrastructure but also at nature-based alternatives. The *Lifelines* report published by the World Bank highlights five recommendations to ensure that infrastructure systems become more reliable and resilient, contributing to development, growth, and economic success:

1. **Get the basics right:** Ensuring that infrastructure assets are well designed, operated, and maintained.
2. **Invest in project preparation**: Increasing early stage funding for resilient infrastructure design can optimize costs over the entire lifetime.
3. **Build institutions for resilience**: Coordinating the actions of the many stakeholders involved in infrastructure design and operations and mobilizing adequate human resources.

4. **Create regulations and incentives for resilience:** Ensuring that all actors consider the full cost of infrastructure disruptions on people, firms, and government.
5. **Improve decision-making**: Strengthening decision-making capacities and providing appropriate data on natural hazards and climate change.

Reliable and resilient infrastructure is necessary for economic prosperity and a high living standard everywhere. Consequently, disruptions of infrastructure are costly, and not just in monetary terms; they hurt people. Increasing the resilience of infrastructure, therefore, not only makes infrastructure systems and assets more durable, but it also saves people's lives and enables firms to operate more efficiently. Resiliency will become even more important in the future because the changing weather and climate patterns associated with climate change will put more stress on all infrastructure systems.

This paper highlights different strategies to increase the resiliency of infrastructure systems. Prior to any investment, a thorough planning phase is needed. This requires detailed data on climate and weather patterns, as well as on existing infrastructure. Making infrastructure more resilient does not necessarily mean redundancy of all assets, but rather redundancy at the right nodes within each infrastructure network. Furthermore, it is important to spend smarter, rather than simply spending more. Considering nature-based alternatives to new hard infrastructure, focusing on maintenance, and improving governance are all possible strategies to improve resiliency at cost-efficient levels.

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