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Background Paper

Strengthening New Infrastructure Assets

A Cost-Benefit Analysis

Stephane Hallegatte

Julie Rozenberg

Jun Rentschler

Claire Nicolas

Charles Fox

WORLD BANK GROUP

Climate Change Group

Global Facility for Disaster Reduction and Recovery

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Abstract

This paper explores the benefits and the costs of strengthening infrastructure assets to make them more resilient, reducing the repair costs and infrastructure disruptions caused by natural hazards. Strengthening infrastructure assets in low- and middle-income countries would increase investment needs in power, transport, and water and sanitation by between \$11 billion and \$65 billion a year, i.e. 3 percent of baseline infrastructure investment needs. The uncertainty pertaining to the costs and benefits of infrastructure resilience makes it difficult to provide a single estimate for the benefit-cost ratio of strengthening exposed infrastructure assets. To manage this uncertainty,

this paper explores the benefit-cost ratio in 3,000 scenarios, combining uncertainties in all parameters of the analysis. The benefit-cost ratio is higher than 1 in 96 percent of the scenarios, larger than 2 in 77 percent of them, and higher than 4 in half of them. The net present value of these investments over the lifetime of new infrastructure assets—or, equivalently, the cost of inaction—exceeds \$2 trillion in 75 percent of the scenarios and \$4.2 trillion in half of them. Moreover, climate change makes the strengthening of infrastructure assets even more important, doubling the median benefit-cost ratio.

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Strengthening new infrastructure assets: A cost-benefit analysis

Stephane Hallegatte¹, Julie Rozenberg¹, Jun Rentschler¹, Claire Nicolas¹, Charles Fox¹

¹ The World Bank, Washington DC, USA

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Introduction

There have been many calls to make infrastructure systems more resilient, in part triggered by recent large-scale disasters. However, it is not straightforward to evaluate the costs and the benefits of more resilient infrastructure and make a quantified economic case for investing more in this domain.

Two challenges make such an assessment particularly difficult. Firstly, the cost of making new infrastructure more resilient depends on the type and quantity of infrastructure that is being built, which is very uncertain and depends on many external factors. Secondly, there are large uncertainties on the cost of making infrastructure more resilient, as well as the effect of such efforts on future repair and maintenance costs, and on the future frequency and duration of infrastructure disruptions. As a result, providing a single estimate of the benefit-cost ratio or the economic benefit from more resilient infrastructure has been difficult.

To provide new evidence on this issue, this paper proposes a cost-benefit analysis with a systematic exploration of the large uncertainty that surrounds many parameters of the analysis, and explores the desirability and robustness of more resilient investment, using principles inspired from the robust decision-making methodology (Lempert et al. 2006).

It starts from a set of scenarios on future infrastructure investments, from Rozenberg and Fay (2019). Then, it reviews the technical options (and their associated costs) to make infrastructure more resilient, based on a study by Miyamoto International (2019). It applies this incremental cost to the baseline investment needs scenarios developed by Rozenberg and Fay. An exploratory modelling approach considering thousands of scenarios is then used to explore the benefit-cost ratio of these options.

Future infrastructure investment needs

Rozenberg and Fay (2019) uses 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 between 2 percent and 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 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.

Table 1. Infrastructure spending on capital and maintenance needs in low- and middle-income countries between 2015 and 2030, by sector

<i>Sector</i>	<i>% of GDP</i>		<i>US\$, billions</i>	
	<i>Capital</i>	<i>Maintenance</i>	<i>Capital</i>	<i>Maintenance</i>
Electricity	2.2	0.6	780	210
Transport	1.3	1.3	420	460
Water and sanitation	0.55	0.75	200	70
Flood protection	0.32	0.07	100	20
Irrigation	0.13	—	50	—
Total	4.5	2.7	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. Under this assumption, countries take long-term climate goals into account now to avoid expensive stranded assets later; they invest now in renewable energy; they combine transport planning with land use planning, resulting in denser cities and cheaper and more reliable public transport; and they develop reliable railway systems that freight haulers find attractive. Decentralized technologies, such as minigrids for electricity and water purification systems powered by renewable energy, would be deployed in rural areas.

However, 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 1).

These estimates do not consider the need to build infrastructure systems that are resilient to natural hazards and adapted to climate change. The topic of this paper is to assess how these estimates change if infrastructure assets and systems are built using stronger and more resilient design, and to determine whether doing so is cost-efficient.

Engineering options to make assets more resilient

Interventions to make assets more resilient include using alternative materials, digging deeper foundations, elevating assets, building flood protection around assets, or adding redundancy into designs. Deeper foundations for power plants, windmills, or water treatment plants are often needed to protect them against liquefaction caused by earthquakes. Better materials for wind turbines, cell towers, and transmission and distribution systems can increase their resistance to strong winds and lengthen their lifetime. Increasing the redundancy of components of water and wastewater treatment plants by adding backup components can improve the performance of plants during earthquakes. Building higher dikes around water treatment plants and nuclear plants is the best option for protecting them against floods.

Miyamoto International (2019) presents a high-level assessment of the costs and benefits of these various technical and engineering options. The additional cost of making assets stronger in the face of natural hazards depends on the hazard and the type of asset. Increasing the flood resilience of a road

through wider diameter drainage pipes or trenches costs a small percentage of the road's value, while increasing the flood resilience of a railway by elevating it costs 50 percent of its value. And protecting a hydropower plant against earthquakes by installing the proper anchorage and seismic components costs 20 percent of its value, whereas protecting a hydropower plant against flooding through bigger spillway capacity costs only 3 percent of its value (Miyamoto International 2019).

Improved quality control is required to ensure that an asset is built and maintained to expected standards. Miyamoto International (2019) estimates that this quality control costs from 1 percent to 5 percent of the value for most assets and hazards, but it can cost up to 15 percent (e.g. ensuring that drainage systems can cope with earthquake motion, and that highway systems can cope with flooding). This quality control would accompany the good procurement practices that are key to lower infrastructure construction costs.

The options explored in Miyamoto International (2019) have been selected because they are realistic, and can make assets more resilient in low- and middle-income countries. However, they are not necessarily the ones that will reduce risk the most, and they do not guarantee that assets cannot be damaged by natural hazards. Many rich countries like Japan implement technical solutions that go beyond—and are more expensive than—the set of solutions considered in this analysis.

The cost of increasing resilience

The next question then becomes, by how much would estimates of future infrastructure investment needs change if infrastructure systems were designed and built in a more resilient manner, through the technical and engineering solutions identified in Miyamoto International (2019)?

To answer this question, we take the infrastructure spending scenarios developed by Rozenberg and Fay (2019) and for each asset type, each hazard, and in each scenario, we apply the incremental cost of resilience given by Miyamoto International (2019). For example, in the transport sector we apply a different incremental cost of flood resilience for airports, railways, urban public transit, highways, or rural roads. The overall cost of resilience will thus depend on the types of investments in the initial scenario (a scenario that represents an investment shift towards more rail will have a higher resilience cost than a scenario where transport investments are focused on roads). As a consequence, we present a range of resilience costs that comes from the range of possible infrastructure spending in Rozenberg and Fay's scenarios.

For each scenario we also assess the overall risk reduction associated with these investments, still using the estimates given by Miyamoto International (2019). Here, again, the benefits depend on the type and quantity of infrastructure investments that are realized.

Because the incremental costs of making assets more resilient can be significant, it is important to target strengthening to areas where exposure to natural disasters is high. Ideally, infrastructure standards and codes should be asset and localization specific. Any effort to design a road should account for the hydrological and hydraulic data and climate model results at the location of the road in order to include in the design the range of impacts that climate change can have on the probability of flood events in the future. For electricity distribution systems—because they are particularly vulnerable to wind from storms, hurricanes, and typhoons—historical data and model results on wind velocities with hour-level

resolution could be used for a geospatial analysis to inform risk and design standards in many regions of the world. Data on water availability for cooling is also central to planning for electricity generation.

In each sector, and for all spending scenarios, we thus explore two extreme scenarios in terms of the knowledge on the spatial distribution of natural hazards and the ability to target strengthening to the places exposed to them.

- In the first scenario, it is assumed that the location and intensity of the hazard are perfectly known, now and in the future, and that different standards can be applied in different locations, depending on the level of risk.
- In the second scenario, it is assumed that the hazard is unknown, or too uncertain to be acted on, and that a uniform standard has to be applied to the full network.

Results for these two scenarios are compared here for three infrastructure systems: power, transport, and water and sanitation.

For the first set of scenarios, it is assumed that future infrastructure assets are exposed in a similar fashion to the existing infrastructure on average in each region (in other words, the sites available for future infrastructure construction are exposed to the same level of hazards, on average, as the sites already in use). We use the exposure to natural disasters calculated by Koks et al (2019) for transport and Nicolas et al (2019) for power. For water and sanitation, since we have no exposure data, we assume that the infrastructure has the average exposure of transport and power infrastructure in each region.

Power

In the power sector, baseline investment needs range from \$298 billion to \$1 trillion a year in low- and middle-income countries between 2015 and 2030 assuming current resilience levels. The position within this range depends on energy efficiency, and the timing of the transition towards carbon-free power generation (which creates stranded assets, such as coal power plants that need to be decommissioned before the end of their lifetime). An additional \$106 billion and \$282 billion a year would be needed for maintenance. How does building in more resilience to power systems increase these costs?

- *Scenario 1.* If only the assets exposed to hazards are made more resilient to those hazards, the incremental cost would be between \$9 billion and \$27 billion a year (depending on the initial spending scenario), which represents a 3 percent cost increase on average across the spending range, and a 6 percent cost increase in the most expensive case. These investments would reduce the risk of damage by a factor of two to three for new infrastructure assets.
- *Scenario 2.* If instead all new power assets were made more resilient to wind, floods, and earthquakes, because the spatial distribution of natural hazards is unknown, then an additional \$96 billion to \$296 billion a year would be needed. This is a 30 percent increase in capital cost on average over the spending range, and a 10-fold increase compared with that in the scenario for which hazard data are available.

Transport

In the transport sector, baseline investment needs—with current resilience standards—could range from \$157 billion to \$1.1 trillion a year between 2015 and 2030 in low- and middle-income countries. The exact value would depend on the choice of mode (such as personal cars versus public transit in cities) and on the policies put in place to encourage those needing transport to switch to rail and public

transportation. In addition, between \$550 billion and \$700 billion would be needed every year to maintain the existing and new transport infrastructure in low- and middle-income countries by 2030, bringing the total annual spending needs to between \$700 billion and \$1.8 trillion. How would those costs increase to make transport systems more resilient?

- *Scenario 1.* The incremental cost of making new exposed transport assets more resilient to floods and landslides lies between \$860 million and \$35 billion depending on the baseline spending scenario. This is a 0.6 percent increase in cost on average across the spending range and potentially a 5 percent increase in the most expensive case. These investments would reduce the risk of damage for new infrastructure by a factor of two.
- *Scenario 2.* If instead all new transport assets were made more resilient to floods and landslides regardless of their exposure, the incremental cost would be from \$8 billion to \$350 billion a year. This is a 5.5 percent increase in cost on average across the spending range, but potentially a 17 percent increase in the most expensive case for many rail investments.

Water and sanitation

In the water supply and sanitation sector, the cost of providing universal access to safe water and sanitation in low- and middle-income countries by 2030, with the current resilience level, would range from \$116 billion to \$229 billion a year for capital investments and from \$32 billion to \$69 billion a year for maintenance. How would those costs increase to make water and sanitation systems more resilient?

- *Scenario 1.* The cost of protecting new exposed water assets would be between \$0.9 billion and \$2.3 billion a year (assuming that on average water and sanitation infrastructure has the same exposure to earthquakes as transport and power assets). These investments would reduce the risk of damage to new infrastructure by 50 percent.
- *Scenario 2.* Instead, if all water assets were made more resilient to floods, an additional \$2 billion to \$5 billion a year would be required. This estimate represents a 1.1 percent to 2.2 percent increase in capital costs. Increasing the resilience of these assets to earthquakes would require an additional \$8 billion to \$20 billion a year (or between 5 percent and 9 percent of capital investment needs).

Summing up

Unfortunately, similar estimates were not possible for telecommunications, and these numbers only include low- and middle-income countries. Yet this exercise provides two important insights.

First, there is huge value in knowing the spatial distribution of natural hazards, including climate change. Focusing the strengthening of infrastructure assets on exposed assets reduces total annual costs from between \$120 billion and \$670 billion to between \$11 billion and \$65 billion (figure 1). The savings from targeting the infrastructure assets most exposed appear to be orders of magnitude larger than the costs of data collection and modeling that would be required to improve knowledge of current and future hazards. Indeed, a global platform like Think Hazard! (Fraser 2017) costs a few million dollars to create and maintain. At most, creating high-resolution digital elevation models and hazard maps for all cities in low- and middle-income countries would cost a few hundred million dollars (Croneborg et al. 2015).

Figure 1. The incremental cost of increasing the resilience of future infrastructure investments is significantly reduced if asset exposure is known

Note: Cost is the average annual capital investment cost between 2015 and 2030. The circles represent the median and the vertical bars represent the full range of possible incremental costs.

Second, the cost of building the resilience of infrastructure assets in low- and middle-income countries is small compared with total infrastructure needs, provided the right data and approaches are available.

Increasing the resilience of only the assets exposed to hazards would increase investment needs in power, transport, and water and sanitation by between \$11 billion and \$65 billion a year. While not negligible, this is only around 3 percent of baseline infrastructure investment needs and less than 0.1 percent of the GDP of low- and middle-income countries. Therefore, making infrastructure more resilient does not affect current affordability challenges for new infrastructure, and it would decrease the risk of damage for new infrastructure by a factor of between two and three.

The benefit-cost ratio of increasing resilience

To assess the benefit of increasing infrastructure resilience, we consider: (1) reduced repair needs due to damages from natural hazards, based on a global risk assessment for transport and generation assets (Koks et al. 2019; Nicolas 2019); (2) reduced infrastructure service outages, based on estimate of their impact on firms (Rentschler et al. 2019) and households (Obolensky et al. 2019).

The challenge lies in the large uncertainties in each of the estimates, and the fact that most of them are partial, either in terms of sectors (with telecommunication missing in all estimates), countries (with most low- and middle-income countries included, with various coverage depending of the estimates), and channels (with, for instance, the impact of infrastructure disruptions on innovation and investment missing).

Another issue is that estimates for the cost of more resilient infrastructure are considering only the strengthening of infrastructure assets, while other options like redundancy, diversification, or nature-based solutions can reduce the cost of resilient infrastructure services quite significantly. In parallel, the report also highlights opportunities for reducing the vulnerability of households and firms to

infrastructure disruptions. These options, if implemented, have the potential to reduce the benefits from more resilient infrastructure systems.

Methodology

To provide insights on the economic value of more resilient infrastructure, in spite of these uncertainties, a systematic exploration of the possible benefit-cost ratios is performed. We create 3000 scenarios, varying all the parameters of the analysis in a simple model.

Each scenario has a constant economic growth from now to 2100, ranging from 2 to 6 percent per year, and an amount of investment in infrastructure ranging from 2 to 7 percent of GDP per year, based on the scenarios from Rozenberg and Fay (2019). These investments are added to the current infrastructure stock – whose value is estimated between \$10,000 and \$20,000 billion – which is assumed to depreciate at a rate between 0.5 and 3 percent per year.

On top of these investments, the model assumes an incremental cost to strengthen infrastructure, based on estimates from (Miyamoto 2019) applied to the structure of baseline investments. Depending on the structure of future infrastructure investments (e.g., the fraction of road vs. rail in transport investments), the incremental cost of more robust assets may range from 1 to 5 percent of the baseline cost.

Then, avoided asset losses are estimated. Current risk levels for transport and power generation have been estimated at \$18 billion per year, for low- and middle-income countries. Adding transmission and distribution, water supply and sanitation, and telecommunication, it is assumed that total risk ranges from \$20 to \$60 billion per year, with a best guess at \$40 billion.

Future asset losses are changing over time as a function of the increase in the stock of infrastructure assets, the fraction of old (higher vulnerability) to new (lower vulnerability) assets, and the impact of climate change. Here, climate change is assumed to increase asset losses by between 0 and 3 percent per year, to represent the uncertainty on future climate change itself.

The economic cost of current infrastructure disruptions is estimated between \$400 and \$600 billion, based on (Rentschler et al. 2019; Obolensky et al. 2019). Because these estimates are incomplete, the higher range of this value is increased to \$1,000 billion per year in this analysis. Based on a collection of case studies, the fraction of the disruptions due to natural hazards is estimated between 5 percent (the value in Bangladesh, where most power outages are due to system failure) and 50 percent (a value that is common for power in developed countries and is observed in Tanzania). The cost of these outages due to natural hazards are assumed to increase like the GDP in low- and middle-income countries, with an additional impact of climate change ranging from zero to 3 percent per year.

Table 2. List of model parameters, range of possible values considered, and sources.

Parameter	Best guess	Minimum	Maximum	Source
Global economic growth	4 percent	2	6	Adapted from the Shared Socioeconomic Pathways
Initial infrastructure stock in LMIC	\$15,000 billion	\$10,000 billion	\$20,000 billion	(Rozenberg and Fay 2019)
Annual investment in infrastructure assets in LMIC, in 2020	4.5	2 percent of GDP per year	7 percent of GDP per year	(Rozenberg and Fay 2019)

Average annual infrastructure asset losses due to natural hazards	\$40 billion per year	\$20 billion per year	\$60 billion per year	(Koks et al. 2019) for transport ; (Nicolas 2019) for generation. Not estimated for power T&D, water supply and sanitation, and telecommunication
Total economic cost from infrastructure disruptions in LMIC	\$500 billion per year	\$300 billion per year	\$1,000 billion per year	(Rentschler et al. 2019) for firms; (Obolensky et al. 2019) for households. Many missing sectors and channels.
Fraction of infrastructure disruptions due to natural hazards	20 percent	5 percent	50 percent	(Rentschler, Obolensky, and Kornejew 2019) for power; for other sector, see a review of evidence and case studies in (Braese, Rentschler, and Hallegatte 2019).
Incremental cost to strengthen new infrastructure assets	3 percent	1 percent	5 percent	Based on (Miyamoto 2019)
Reduction in vulnerability through strengthening	2.5	2	3	Based on (Miyamoto 2019)
Impact of climate change	1.5 percent	0 percent	3 percent	Authors, based on (Field and Barros 2014)

Finally, all costs and benefits are discounted, using a discount rate based on a Ramsey rule and the assumed average rate of economic growth in low- and middle-income countries (with an elasticity of the marginal utility of consumption taken at 1.5 and a pure preference for the present at one percent).

Table 2 shows the list of parameters, with the range of values that are explored, and the source of evidence. For the average annual asset losses due to natural hazards and the total economic cost from infrastructure disruptions, the maximum value is increased compared to some of the sources, to account for the fact that estimates are incomplete in terms of country, sector, and channel coverage.

3000 scenarios are created by varying the values of all parameters within their range, assuming a uniform probability of occurrence in each range (a Latin hypercube sampling was used). For each scenario, a simple model is used to calculate (1) the benefit and cost of strengthening new infrastructure assets starting in 2020, and the resulting benefit-cost ratios; and (2) the cost (or benefit) to delaying action until 2030, continuing to build business-as-usual infrastructure asset until then.

Results

In the ‘best guess’ scenario, the benefit cost ratio of strengthening new infrastructure assets is equal to 2.3, with the discounted benefits reaching \$4,416 billion for a cost of \$1,881 billion. The cost of inaction (or the net present value of acting) is therefore around \$2,535 billion. Figure 1 shows the temporal pathways of the costs and benefits of the measure, for action starting in 2020. Assuming constant investments relative to GDP over the period, the cost of strengthening new infrastructure assets starts at \$45 billion per year and increase with GDP. Starting at this time, the benefits in terms of avoided

asset losses and avoided outages start to increase over time, with GDP and the stock of more resilient infrastructure, exceeding annual costs in 2027 for a start in 2020.

However, results from the best guess scenario should be used with care, and it is better to explore the range of possible results. Figure 2 provides an illustration of the results for the 3000 scenarios. It maps the benefit-cost ratio of strengthening infrastructure assets (indicated by the color of the dots), against the fraction of today’s disruptions that are due to natural hazards (on the x-axis) and the incremental cost of strengthening infrastructure (on the y-axis).

Figure 1 – Temporal pathways of costs and benefits of strengthening new infrastructure assets

Figure 2. The benefit-cost ratio of strengthening infrastructure is high in most scenarios.

Note: The figure shows the 3000 scenarios, mapped as a function of the fraction of today's disruptions that are due to natural hazards, and the incremental cost of strengthening infrastructure. The color of each dot corresponds to the benefit-cost ratio, as described by the color bar.

The full range of model results suggests that strengthening new infrastructure asset is a robust solution, with high economic returns. Out of 3000 scenarios, 96 percent have a benefit-cost ratio larger than one, 77 percent a benefit-cost ratio larger than 2, 55 percent have a benefit-cost ratio larger than 4, and 25 percent have a benefit-cost ratio higher than 6.

The net present value of these investments, over the lifetime of new infrastructure assets, exceeds \$2 trillion in 75 percent of the scenarios and \$4.2 trillion in half of them (figure 3). (Equivalently, the median cost of inaction is \$4.2 trillion.)

The 4 percent of scenarios with a benefit-cost ratio below one, and therefore in which strengthening new asset is not desirable, are scenarios in which all estimates are consistently biased in the same direction, i.e. in which the cost of strengthening is at the top of the range, the impact of hazards on infrastructure assets and disruptions is at the bottom of the range, and the socioeconomic consequences of disruptions are the lowest (Figure 2). The distribution of losses and benefits is highly asymmetric: even in the unlikely worst-case scenario, the benefit-cost ratio does not go below 0.7, and the net present value of the losses do not exceed \$1 trillion (compared with benefit-cost ratios higher than 15 and total benefits exceeding \$20 trillion in the best cases).

Moreover, climate change makes the strengthening of infrastructure assets even more important. Without climate change, the median benefit-cost ratio would be equal to 2, but it is doubled when climate change is considered. And the fraction of scenarios in which strengthening infrastructure is not profitable is decreased from 14 to 4 percent when climate change is taken into account.

Figure 3. Histogram of the net present value of strengthening infrastructure assets, with 3000 scenarios covering a large range of possible parameter values.

Figure 4. Histogram of the cost of delaying action to 2030, with 3000 scenarios covering a large range of possible parameter values.

Overall, strengthening infrastructure assets seem a very robust solutions that is very likely to be cost-effective, has a high likelihood to generate very large benefits, and cannot generate massive losses, even in the worst-case scenarios.

The urgency of designing better infrastructure is also evident in the simulations (Figure 4). The cost of delaying action to 2030 is positive in 93 percent of the scenarios. The only scenarios in which delaying action is preferable are scenarios in which strengthening infrastructure assets has a benefit-cost ratio below or very close to one. This happens when the cost of strengthening is very high (close to 5 percent), asset losses due to disaster are small, few infrastructure disruptions are explained by natural hazards, and climate change does not increase the frequency and magnitude of hazard impacts on infrastructure assets. The median cost of delaying action to 2030 is \$1 trillion.

Conclusion

While it appears out of reach to estimate the precise benefit-cost ratio of strengthening infrastructure assets, it is possible to show that (1) this is a very robust option, which is very unlikely not to reveal cost-effective, and (2) acting earlier if preferable to delaying action. Moreover, the desirability of investing in the options to make infrastructure assets more resilient is underestimated in this analysis, since only the disruptions due to natural hazards are considered. In practice, more robust assets are also likely to resist better to other failures (including voluntary ones), leading to larger benefits than those estimated here.

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