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Climate risk and response: Physical hazards and socioeconomic impacts

Will infrastructure bend or break under climate stress?

Case study
June 2020

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Introduction to case studies

In January 2020, the McKinsey Global Institute published *Climate risk and response: Physical hazards and socioeconomic impacts*. In that report, we measured the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. We explored risks today and over the next three decades and examined specific cases to understand the mechanisms through which climate change leads to increased socioeconomic risk. This is one of our case studies, focused on infrastructure.

We investigated cases that cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of McKinsey Global Institute research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We found these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds (Exhibit 1). As such, these cases represent leading-edge examples of climate change risk. Each case is specific to a geography and an exposed system, and thus is not representative of an "average" environment or level of risk across the world. Our cases show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). We typically define the climate state today as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. Such an "inherent risk" assessment allows us to understand the magnitude of the challenge and highlight the case for action. (We also choose a sea level rise scenario for one of our cases that is consistent with the RCP 8.5 trajectory). Our case studies cover each of the five systems we assess to be directly affected by physical climate risk, across geographies and sectors. While climate change will have an economic impact across many sectors, our cases highlight the impact on construction, agriculture, finance, fishing, tourism, manufacturing, real estate, and a range of infrastructure-based sectors. The cases include the following:

— For livability and workability, we look at the risk of exposure to extreme heat and humidity in India and what that could mean for that country's urban population and outdoor-based sectors, as well as at the changing Mediterranean climate and how that could affect sectors such as wine and tourism.

— For food systems, we focus on the likelihood of a multiple-breadbasket failure affecting wheat, corn, rice, and soy, as well as, specifically in Africa, the impact on wheat and coffee production in Ethiopia and cotton and corn production in Mozambique.

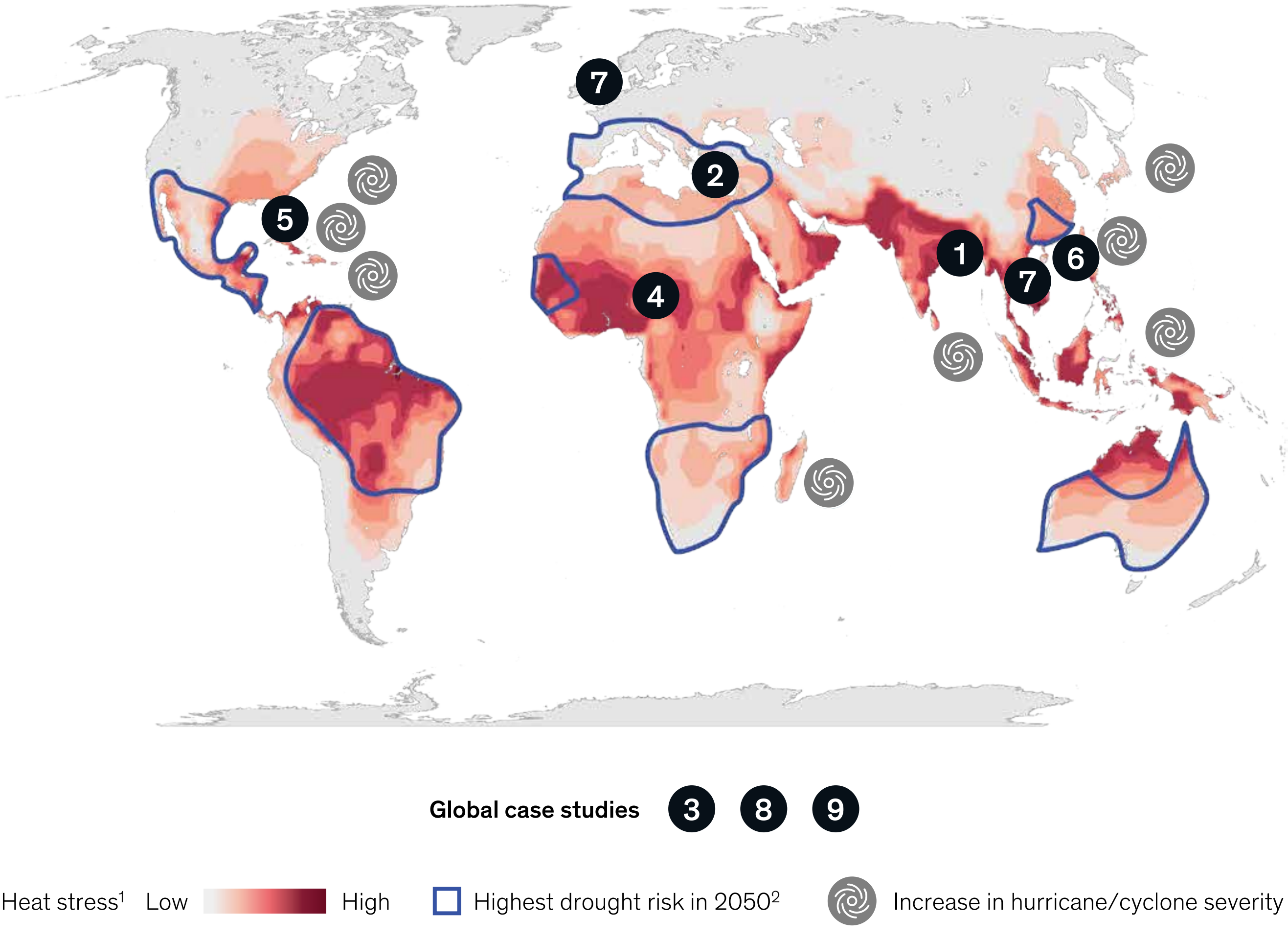
— For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

— For infrastructure services, we examine 17 types of infrastructure assets, including the potential impact on coastal cities such as Bristol in England and Ho Chi Minh City in Vietnam.

— Finally, for natural capital, we examine the potential impacts of glacial melt and runoff in the Hindu Kush region of the Himalayas; what ocean warming and acidification could mean for global fishing and the people whose livelihoods depend on it; as well as potential disturbance to forests, which cover nearly one-third of the world's land and are key to the way of life for 2.4 billion people.

Exhibit 1

We have selected nine case studies of leading-edge climate change impacts across all major geographies, sectors, and affected systems.



Livability and workability	1	Will India get too hot to work?
	2	A Mediterranean basin without a Mediterranean climate?
Food systems	3	Will the world's breadbaskets become less reliable?
	4	How will African farmers adjust to changing patterns of precipitation?
Physical assets	5	Will mortgages and markets stay afloat in Florida?
	6	Could climate become the weak link in your supply chain?
Infrastructure services	7	Can coastal cities turn the tide on rising flood risk?
	8	Will infrastructure bend or break under climate stress?
Natural capital	9	Reduced dividends on natural capital?

1. Heat stress measured in wet-bulb temperatures.
2. Drought risk defined based on time in drought according to Palmer Drought Severity index (PDSI).

Source: Woods Hole Research Center; McKinsey Global Institute analysis

Flooding can disrupt infrastructure like roads, isolating communities.
© Getty Images

Infrastructure

Will infrastructure bend or break under climate stress?

Infrastructure is the backbone of the global economy, a critical enabler of prosperity and growth. It helps to connect people, enhances quality of life, and promotes health and safety. Infrastructure assets typically include buildings and facilities that enable the delivery of power, transportation, water, and telecommunications services. Today the world spends roughly $5 trillion a year on infrastructure, about the same amount as global outlay on real estate.[1] When infrastructure fails, the result is not only direct asset damage but, often, large socioeconomic knock-on effects as services are disrupted.

In recent years, extreme weather events have highlighted infrastructure vulnerabilities. When Hurricane Sandy struck the eastern seaboard of the United States in October 2012, for example, subways, airports, and roads were flooded, causing transportation to grind to a halt. Millions lost power, some for days or weeks, shutting down businesses and creating public safety issues. In addition to winds knocking out one-fourth of cell phone towers in the Northeast, the loss of electricity forced many towers offline after depleting their emergency batteries.[2] Eleven billion gallons of sewage flowed into rivers, bays, and coastal waters, because severe inundation overwhelmed municipal wastewater systems.[3] In total, the storm caused about $70 billion in damages.[4] But despite being one of the costliest and most destructive storms on record, this event was not an aberration. Nine of the costliest mainland US hurricanes on record have occurred in the past 15 years. This is primarily because of continued growth and development in coastal urban areas (with the percentage of the world's population living in coastal areas expected to jump from about 55 percent today to 65 percent by 2040), however, attribution studies have shown that climate change amplified severity for three of the nine storms, and going forward climate change is expected to further intensify these risks.[5]

Infrastructure usually involves large investments in assets that are designed to operate over the long term. Coal-fired plants are designed for 40 to 50 years, for example, and hydropower dams and large geotechnical structures for up to 100 years.[6] To date, the design of these facilities typically has assumed a future climate that is much the same as today's. However, a changing climate and the resulting more extreme weather events mean those climate bands are becoming outdated, leaving infrastructure operating outside of its tolerance levels. This can present direct threats to the assets as well as significant knock-on effects for those that rely on the services those assets deliver. And small increases in climate hazard can have nonlinear effects as tolerance levels for infrastructure are breached. Importantly, both chronic and acute climate hazards can affect infrastructure. Chronic impacts can result when

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1. Including transportation, power, water, telecommunications, social infrastructure (for example, hospitals), oil and gas, and mining. *Bridging infrastructure gaps: Has the world made progress?*, McKinsey Global Institute, 2017.
2. "FCC Chairman Genachowski announces post-Superstorm Sandy field hearings," news release, November 21, 2012, as reported in CNN, 2012, NPR, 2013, and Reuters, 2012.
3. Alyson Kenward, Daniel Yawitz, and Urooj Raja, *Sewage overflows from Hurricane Sandy*, Climate Central, 2013.
4. National Hurricane Center, "Costliest U.S. tropical cyclones tables updated," January 26, 2018.
5. Of the nine costliest hurricanes that have struck the United States over the past 15 years, scientists have investigated the influence of climate change on three: Hurricane Katrina (2005), Hurricane Sandy (2012), and Hurricane Harvey (2017). For all three, climate change was found to have amplified impact severity, whether through high storm surges or increased precipitation. S-Y Simon Wang et al., "Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas," *Environmental Research Letters*, May 2018, Volume 13, Number 5; Jennifer L. Irish et al., "Simulation of Hurricane Katrina (2005) under sea level and climate conditions for 1900," *Climatic Change*, February 2014, Volume 122, Number 4; Ning Lin et al., "Hurricane Sandy's flood frequency increasing from year 1800 to 2100," *Proceedings of the National Academy of Sciences*, October 2016, Volume 113, Number 43; *Global infrastructure outlook*, 2017, Global Infrastructure Hub and Oxford Economics; National Hurricane Center, "Costliest U.S. tropical cyclones tables updated," January 26, 2018.
6. Steve Inskeep and Ashley Westerman, "Why is China placing a global bet on coal?," NPR, April 29, 2019; "Hydroelectric power: A guide for developers and investors, International Finance Corporation, World Bank Group, February 2015.

a hazard occurs regularly, for example the decreasing operating efficiency of the electric grid under high summer temperatures every year. Acute impacts can occur when infrastructure is exposed to an extreme “tail” event such as a 1 percent probability flood that shuts down a city’s entire electrical grid. Worse, climate hazards can create compounding effects due to interactions between physical hazards. For example, sea-level rise amplifies storm surge, which may also grow due to increased wind and storm severity, exposing more assets to direct wave load damage.

In this case study, we examine four critical infrastructure systems—the electric power grid; water storage, treatment, and purification; transportation; and telecommunications—to determine how vulnerable global infrastructure is to a changing climate. We analyze key assets across these infrastructure systems in relation to several major climate hazards. We also examine the impact of rising temperatures on global air travel in more detail.

Overall, we find that climate change could increasingly disrupt critical systems, increase operating costs, exacerbate the infrastructure funding gap, and create substantial spillover effects on societies and economies. We find that there is a range of unique vulnerabilities of different types of infrastructure assets to different categories of climate hazards. Few assets will be left completely untouched. In certain countries, heat-related power outages could increase in severity and may push the grid to cascading failure; aircraft could also be grounded more frequently as both planes and airports cross heat-related thresholds. To help infrastructure investors and owners as well as communities and regions assess, prepare for, and mitigate climate risk, we then outline a framework for action. Many of the adaptation actions suggested will generate significant returns on investment in preventing or reducing damages from climate hazards, and some (for example, early warning systems, better urban design) will have near-term positive returns. Other adaptation efforts, especially those requiring significant capital investment, will be more challenging, and will require alternate financing and public-private collaborations.

The climate risk to infrastructure is both pervasive and diverse

Infrastructure systems and their components are diverse. Some assets might see an order-of-magnitude increase in risk from a specific climate hazard by 2050, while others may be much less affected.[7] Even within a given infrastructure function (power generation, for example), the biggest threats to assets vary significantly based on the technical specifications of asset components and the degree to which these assets will be exposed to changing climate hazards. Understanding these differences is crucial for successful planning. To that end, we have produced a heat map that explores the risk of potential future interruptions from typical exposure to climate hazards by 2030 (Infrastructure-1).

In the four major infrastructure classes, we identify a total of 17 types of assets to evaluate against seven climate hazards: tidal flooding amplified by sea-level rise; riverine and pluvial flooding; hurricanes/typhoons and storms; tornadoes and other wind events; drought; heat (temperature increases in both air and water); and wildfires.[8] Each type of infrastructure system has specific elements vulnerable to specific climate hazards; we map those hazard-infrastructure intersections where risks will most be exacerbated by climate change.

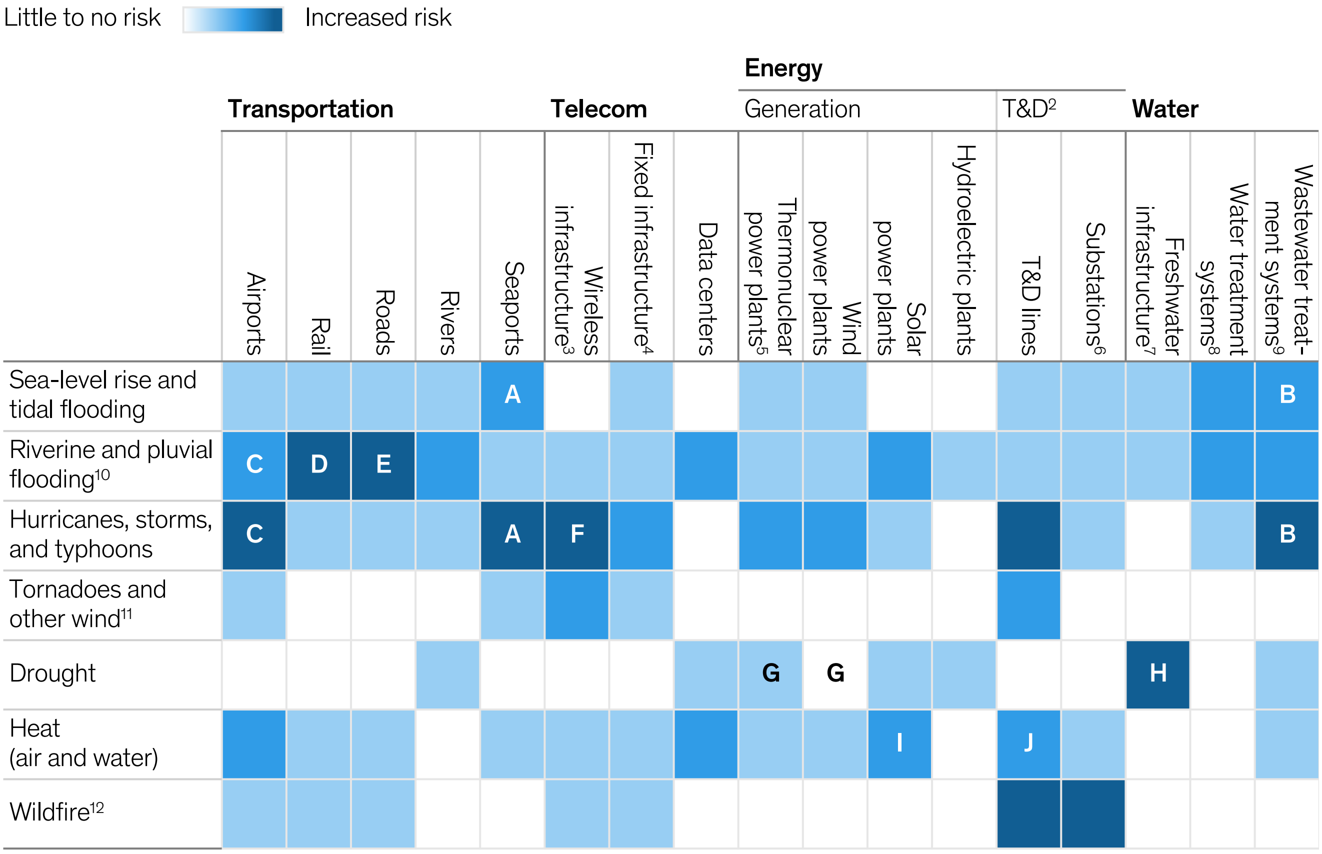
[7] If not indicated differently, we follow standard practice and define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060. Also, if not indicated differently, the climatological analyses in this case use RCP 8.5 to represent the changes in atmospheric greenhouse gas concentrations that could occur absent a mitigation response. Please see technical appendix of the full report for details.

[8] For the hurricanes, storms, and typhoons hazard we look at the combination of increased precipitation and wind speeds, including associated storm surges. Our analysis excluded changes in cold weather storms, given lower confidence in climate change’s effects. While cold weather storms do in fact pose a hazard to infrastructure assets, climate change will diminish rather than amplify these hazards, although not uniformly from a spatial perspective.

Case study Infrastructure-1

Global infrastructure assets have highly specific vulnerability to hazards: at least one element in each type of infrastructure system sees high risk.

Risk Defined as potential future losses as a result of exposure to climate hazards[1]



A. Seaports, by definition, are exposed to risk of all types of coastal flooding. Typically, seaports are resistant and can more easily adjust to small sea-level rise. However, powerful hurricanes are still a substantial risk. In 2005, Hurricane Katrina destroyed ~30% of the Port of New Orleans.

B. Wastewater treatment plants often adjoin bodies of water and are highly exposed to sea-level rise and hurricane storm surge. Hurricane Sandy in 2012 led to the release of 11 billion gallons of sewage, contaminating freshwater systems.

C. Many airports are near water, increasing their risk of precipitation flooding and hurricane storm surge. Of the world's 100 busiest airports, 25% are less than 10m above sea level, and 12—including hubs serving Shanghai, Rome, San Francisco, and New York—are less than 5m. Only a few mm of flooding is necessary to cause disruption.

D. Rail is at risk of service interruption from flooding. Disruption to signal assets in particular can significantly affect rail reliability. Inundation of 7% of the UK's signaling assets would disrupt 40% of passenger journeys. Damage can occur from erosion, shifting sensitive track alignments.

E. Roads require significant flood depths and/or flows to suffer major physical damage, but incur ~30% speed limitations from 0.05m inundation and can become impassable at 0.3m. Compounding effects of road closures can increase average travel time in flooded cities 10–55%.

F. Cell phone towers are at risk from high wind speeds. During Hurricane Maria in 2018, winds of up to 175mph felled 90+% of towers in Puerto Rico. Risks are more moderate at lower wind speeds, with ~25% of towers downed by ~80mph winds during Hurricane Sandy.

G. Wind power plants are highly resistant to drought; thermoelectric power plants, which regularly use water for cooling (seen in >99% of US plants), are at risk during significant shortages.

H. Freshwater infrastructure and associated supplies are highly vulnerable to impact of drought, as seen when Cape Town narrowly averted running out of drinking water in 2018.

I. Solar panels can lose efficiency through heat, estimated at 0.1–0.5% lost per 1°C increase.

J. Transmission and distribution suffers 2 compounding risks from heat. Rising temperatures drive air conditioning use, increasing load. Concurrently, heat reduces grid efficiency.

1. Losses are defined as asset interruption, damage, or destruction. 2. Transmission and distribution. 3. Base substations and radio towers. 4. Including above- and below-ground cable. 5. Including nuclear, gas, and oil. 6. Including large power transformers. 7. Reservoirs, wells, and aquifers. 8. Plants, desalination, and distribution. 9. Plants and distribution. 10. Pluvial flooding is flooding caused by extreme precipitation, independent of the actions of rivers and seas. 11. Including both rain and wind impacts. 12. Wildfire is a derivative risk primarily driven by drought.
Source: Dawson et al., 2016; Federal Communications Commission, 2016; Mobile Association, 2018; *New York Times,* 2006; Pablo, 2005; Prelenato, 2019; Pyatkova, 2019; Xi, 2016; McKinsey Global Institute analysis

To do so, we examined four factors:

— Projected changes in the actual climate hazards due to climate change over the coming decades (for example, will sea levels rise significantly over the time period?)

— Whether infrastructure assets are—or will be—exposed to these physical hazards (for example, are there airports near rising seas?)

— Whether these physical hazards will affect the specific technical parameters of these infrastructure assets, breaching impact thresholds (for example, would sea water on an airport runway affect the airport's operation?)

— What the degree of impact would likely be relative to a world without such climate risks (for example, what will the degree of disruptions to airport operations be relative to how they operate today?)

We evaluated these factors using climate models; reviewing existing studies on climate-infrastructure interactions; speaking with a range of experts to understand the specific technical limitations of different infrastructure components (for example, at what heat level does an energy distribution network lose efficiency? How many millimeters of water on an airport runway before flights are canceled? At what wind speed would a wireless tower be toppled?); and then assessing the degree of impact of these effects on the asset's operation or economics.

The result of this work was to place each infrastructure type along a continuum of risk to both owner-operators of these assets and those who rely on the assets' performance. At the lower-risk end of the spectrum, we would expect minimal effect of climate hazards on the asset economics, or minimal investments required to improve the resilience of such assets. We would also expect relatively little asset downtime when climate hazards do manifest. On the higher risk end of this spectrum, asset economics may shift as infrastructure owners and operators need to invest significant funds in adapting assets to increased climate risks or dealing with frequent or severe asset performance issues. Those who rely on these assets may also expect reliability issues.

Looking at assets in all types of infrastructure sectors, increasing risk from climatic hazards takes the form of both sudden shocks and long-term recurring chronic pressures. While extreme events carry higher risk levels, most assets also have chronic risks that should not be ignored, because they will occur much more frequently and begin to cross operational thresholds that disrupt the productivity of such assets (we explore the impact of rising temperatures on thresholds involving airplanes below). For example, a nuclear power plant could be built with extensive flood defenses or in an elevated location, but it is still subject to long-term efficiency losses if its cooling water rises in temperature.

There is no one dominant hazard for all assets, nor any hazard that the infrastructure sector can ignore entirely. While some hazards appear threatening to more assets (for example, hurricanes and riverine and pluvial flooding), and others (such as wildfires and drought) appear to have smaller reach, no single hazard dominates, and each one presents at least several tangible risks. Overall, we find that many assets could expect a small to moderate increase in risk from climate hazards by 2030. These are risks that will likely result in costs over the lifetime of the asset if not addressed.

Specifics are important because each asset type is exposed to a unique risk profile and climate hazards can vary based on the specific geographical location of an asset. The heat map analysis presented here is based on the change in climate hazards, exposure of assets to these hazards, vulnerability of the assets, and resulting impact. But not all regions are exposed to the same hazards to the same degree. For example, in power plants, a country with high levels of solar energy should be concerned with rising temperatures but may have little to fear from strong winds. In contrast, one with high levels of wind power may face almost no threat from heat but may be at substantial risk from hurricanes.

Our analysis reveals two different sets of risks involving infrastructure: direct (for example, a power plant goes offline because it floods) and indirect (for example, a power plant cannot transmit power because the power transmission lines have gone down). A typical asset's direct risk is estimated in our heat map analysis. But direct vulnerabilities are only half the story. Risk is further exacerbated by the vulnerabilities of a specific infrastructure asset to failures in the infrastructure systems within which that asset is embedded. These dependencies can spread risk. We find that each system (for example, energy, water) has at least one severely vulnerable element. Because of the interdependency of these infrastructure systems, the high-risk assets may represent critical points of failure for the entire system, causing operational losses for all other assets in the chain and knock-on effects for a broader set of institutions and individuals.

Inter-system dependencies also need to be considered and are often harder to preempt. For example, new data centers are typically built away from flood plains but are at risk from power outages in legacy electrical distribution infrastructure. Similarly, a coal-fired power station typically has only 15 days of fuel in storage (often less in times of peak demand) and will have to cease operation if transportation connectivity is cut for longer than its inventory lasts.[9] The recovery of infrastructure after major "tail" events is often hampered by the absence of effective telecommunications. Increasing digitization of control systems in infrastructure is typically increasing inter-system dependencies.

What failure means for assets is also not necessarily comparable. Some assets resist permanent damage easily but have extremely sensitive operating conditions. Others can continue normal operations up to a more substantial threshold but then suffer damage at a faster rate. For example, roads usually cease functionality from only 0.3 meter of floodwater but are usually highly resistant to major damage in the absence of fast water flows. In contrast, electrical substations can continue functioning normally up to their level of waterproofing or defense, but as soon as this threshold is crossed, both cease operating and suffer damage requiring repair.

Risks can be compounded by correlated human actions. Most of the hazards explored in our analysis will also change the behavior of humans, most critically how they interact with infrastructure. Often, these hazards exacerbate the threat. For example, hot weather reduces grid transmission efficiency, but it also leads to increased transmission demand due to increased air-conditioning use, culminating in a combined threat. In drought situations, illegal water drilling can increase, affecting expected reservoir intake and limiting the ability to fairly manage supplies.

9 Fan Ruohong and Teng Jing Xuan, "Coal inventories grow after rough winter," Caixin Global, February 12, 2018.

Finally, exposure trends matter in terms of the damage to infrastructure from physical climate change. For example, we have chosen to model a base case of continued trends in exposure with regards to the use of high-carbon infrastructure. However, as societal expectations change, attitudes about high-carbon uses of infrastructure could change. This may involve driving in higher-occupancy vehicles or using public transportation more often, changing the types of transportation infrastructure that are in most demand. Alternatively, it could reduce the demand for air travel, seen in the concept of "flygskam" or "flight shame." A UBS study found that growth in passenger numbers could halve if current trends continue.[10] We do not model these effects, but they bear consideration.

In this section, we explore more deeply some of the findings summarized in the above heat map analysis, with deep dives by infrastructure system. All systems face a relatively similar magnitude of threat from climate change, but the threat manifests differently: some are more exposed to chronic stresses, others to acute shocks; some bear the impact equally across assets, others have clear points of weakness; some are fast growing with shorter asset lives and higher redundancy, while others are slower paced and rely on large, critical, long-life assets.

The power grid is highly vulnerable to climate risk from both acute and chronic impacts, amplified by fragile components and relatively low redundancy

Power grids, made up of generation, transmission, and distribution components, are essential to the modern economy.[11] Last year the world consumed more than 25,000 terawatt hours (TWh) of electricity, of which nearly 78 percent was generated through thermoelectric plants (coal, oil, nuclear, natural gas), 16 percent from hydropower, and 6 percent from solar photovoltaics and wind.[12] The development of power grids is expected to grow, partly because of economic growth, but also because about 1.1 billion people, or 14 percent of the world's population, lack access to electricity.[13] Electrification is also a likely decarbonization strategy for many sectors. As new grids are added and existing grid infrastructure is upgraded, understanding the extent of climate risks and how to mitigate them will be critical.

The effects of climate-related hazards on the power grid is already apparent. Heat waves in Australia in 2019 caused 200,000 customers in Melbourne to be affected by load shedding.[14] In Europe and the United States, a number of thermoelectric plants and transmission systems have had to shut down or curtail operations due to heat waves, wildfire risk, or concerns that hot-water discharge into already warm rivers or lakes would violate regulations.

Both acute events (for example, flooding, fires, storms), and chronic changes in climatic conditions (for example, heat) can damage the grid. These acute and chronic hazards cause significant direct asset damage and severe service interruptions. Inundation events, whether due to precipitation changes, sea-level rise, or storm surge, pose a significant risk to both generating assets and transmission and distribution lines. For example, 69 power plants were in flooded areas during Hurricane Sandy, and 44 were in flooded areas during Hurricane Irene in 2011. During both hurricanes, eight nuclear power plants had to shut down or reduce service. Extreme storms, which usually combine some amount of high wind and inundation, pose a threat to generation, transmission, and distribution assets. For example, during Hurricane Harvey in 2017, wind and flooding knocked down or damaged more than 6,200 distribution poles and 850 transmission structures.[15]

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10 "'Flight shame' could halve growth in air traffic," BBC News, October 2, 2019.
11 In this analysis we exclude energy storage, due to its comparative rarity.
12 International Energy Agency, *World energy outlook 2019,* 2019.
13 Ibid.
14 ABC News (Australia), "Power outages hit Melbourne, regional Victoria as state swelters through extreme weather," January 25, 2019.
15 Sarah Brody, Matt Rogers, and Giulia Siccardo, "Why, and how, utilities should start to manage climate-change risk," April 2019, McKinsey.com.

Heat is the biggest strain on the grid. Higher temperatures lower generation efficiency, increase losses in transmission and distribution, decrease the lifetime of key equipment including power transformers, boost peak demand, and force certain thermoelectric plants offline.[16] Day to day, these pressures cause rising operating costs and reduced asset life. In rare cases, these stressors can overwhelm the grid and lead to load shedding and blackouts. Higher air temperatures reduce efficiency and grid capacity, while often increasing cooling demand. High air temperatures can also result in reduced peak energy generation capacity through efficiency loss or, in certain instances, curtailment (namely with respect to water-cooled thermoelectric plants), efficiency losses in the transmission and distribution network, and less transmission and distribution of power flow capacity in lines and transformers. Especially in the summer months, extreme heat can result in an increase in peak load from greater use of air-conditioning. The combined effects can narrow the grid's planned reserve margin. When this margin reaches 5 percent, the situation is considered critical, and when it reaches zero, load must be shed in the form of service interruptions (outages) or brownouts (voltage reductions).

In 2018, Finnish utility Fortum Oyj had to cut electricity production during a heat wave. Days later, Vattenfall AB shut down a unit at Scandinavia's largest power plant in Sweden for the same reason.[17] Additionally, higher temperatures can induce mechanical failures; for example, local distribution transformers will shut off or stop working in heat waves, or overhead lines might sag so much that they touch a tree and trip, increasing fire risk. Blackouts occur only when load shedding cannot be managed: if one line fails, its load must be shifted to another line, but if those lines are congested or offline (due to scheduled maintenance or a downed tree, for example), they fail as well. This can cause cascading line failures, leading to a system-wide blackout.

So far, the costs associated with extreme heat and other climate hazards for the power grid have been relatively small. One study estimates that power outages in general, not specifically from climate events, cost the United States $104 billion to $164 billion annually.[18] Full blackouts, the most severe form of power outage, generally cause significant costs for utilities, consumers, and businesses, but they tend to be far less common.[19] Power outages of any kind from heat waves are relatively rare, constituting only about 2 percent of power outages reported in the United States (equivalent to an estimated one to two per year from 2000 to 2020).[20]

However, instances and associated costs of disruptions to the power grid are likely to rise as temperatures increase. As average heat levels increase, so does the frequency of extreme heat events and the duration of less severe periods of higher than average heat that cause efficiency losses. The intensity of these events will also increase as the distribution of temperatures shifts to the right. Hot periods will be hotter than systems are used to, increasing the degree of failure and thus the associated recovery times, lost revenues, and repair costs. For example, California's Fourth Climate Change Assessment states that by 2060, 5% p.a. probability heat waves in Los Angeles County may reduce overall grid capacity by 2 to 20 percent.[21]At a substation level, overloading would increase significantly, pushing some substations in to automatic shut off mode, disconnecting entire neighborhoods and leaving others with significant load shedding.

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16 Plants that discharge heated wastewater into rivers can be curtailed or taken offline if discharge would violate thermal regulations.

17 Michael Copley, Esther Whieldon, and Yannic Rack, "Climate change turns up the heat for Europe's nuclear plants," S&P Global, July 1, 2019; Lefteris Karagiannopoulos, "In hot water: How summer heat has hit Nordic nuclear plants," Reuters, August 1, 2018.

18 Richard J. Campbell, *Weather-related power outages and electric system resiliency*, Congressional Research Service, August 28, 2012.

19 *Final report on the August 14, 2003 blackout in the United States and Canada: Causes and recommendations*, U.S.-Canada Power System Outage Task Force, April 2004; David E. Newman et al., "Exploring complex systems aspects of blackout risk and mitigation," *IEEE Transactions on Reliability,* March 2011, Volume 60, Number 1.

20 Climate Central, 2018.

21 Daniel Burillo, et al., *Climate change in Los Angeles county: Grid vulnerability to extreme heat,* A Report for: California's Fourth Climate Change Assessment, August 2018.

There are several adaptation measures that can be taken to improve the ability of energy systems to operate effectively in shifting climate bands, some of which can also further emissions reductions efforts. For example, distributed generation systems can reduce reliance of some energy consumers on central generation and transmission systems, and often use lower carbon forms of energy generation (for example, rooftop solar). Technical modifications to existing systems will also be a critical component of adaptation, to ensure that they can perform effectively within higher levels of heat overall, and in acute heat waves in particular. Exposure reduction will also be a critical component, including locating generation and transmission facilities in areas where they are less susceptible to fires, floods, and wind; and investing in infrastructure that prevents flooding of distribution assets in cities.

Transportation infrastructure is widely distributed, is interconnected, and can be affected by relatively minimal climate hazards, resulting in significant societal impacts
Roads, rail, airports, rivers, and ports connect the global economy and facilitate trade and the movement of people. In 2018 alone, 45 million commercial flights operated; there were 64 million kilometers of road and one million kilometers of rail; and 10.7 billion tons of cargo shipped through ports.[22] Covering vast areas and connecting remote communities, transportation infrastructure assets often have limited flexibility, making it difficult to avoid climate hazards. The result is significant exposure to risks, particularly of service interruption. As hazards increase, more assets will be exposed. In the United States, 13 major airports have at least one runway within 12 feet of current sea levels, exposing them to sea level rise. Increased precipitation and flooding may compromise the structural viability of transportation system foundations, as will thawing permafrost in the Arctic. Extreme winds can compromise bridge stability, damage signage, and increase debris.[23]

In developed countries, some transportation infrastructure such as roads, bridges, and ports are typically strong and resistant to significant physical damage outside of extreme situations. Most, however, are highly sensitive to disruptions in their operation outside of the thresholds they were designed within. For example, a temperature of 39 degrees Celsius or more can render intercity train tracks unsafe; flooding of a metro station can close an entire underground system; and extreme heat waves can bring air travel to a halt (see Box 1, “How disruptive could extreme heat be to global air travel?”). Flooding can undermine rail infrastructure—for example, in 1997 in Arizona, floods derailed an Amtrak passenger train, injuring 183—or disrupt rail communications. Roads and bridges are similarly threatened by high waters. One study suggests that one or more UK road bridges may fail due to high river flows as often as once every 2.6 years.[24] In 2011, flooding in eastern China caused major damage to 28 rail links, 21,961 roads, and 49 airports.[25]

22 CIA World Factbook—Roadways, 2013; World Bank—Rail lines (2019); *Review of Maritime Transport 2018,* United Nations Conference on Trade and Development, 2018.1
23 *Integrating climate change into road asset management*, World Bank, April 2017.
24 Zora van Leeuwen and Rob Lamb, *Flood and scour related failure incidents at railway assets between 1846 and 2013*, JBA Trust, April 2014.
25 Hu Xi, *Special report: Climate change poses grave threats to China’s essential infrastructure*, China Dialogue, 2016.

Due to the interconnected nature of transit, the failure of one transportation element has cascading effects across a network. If a road is flooded, travelers shift to alternate routes, increasing traffic. Even light to moderate flooding in road systems can cause significant congestion, extending trip times in a city by up to ~30 percent.[26] Flooding of just 7 percent of the United Kingdom's signaling assets would disrupt 46 percent of passenger journeys.[27]

In response to these threats, there are a range of potential adaptation measures. One adaptation measure that could improve the resilience of entire transportation systems is densification. By reducing dispersion of homes and workplaces, the degree of transportation infrastructure required—and the associated costs of protecting this infrastructure—is reduced. Another method of adaptation is increasing detection of potential faults in transportation infrastructure. Recent technologies, such as those that can detect cracks along extensive railway networks or sensor layers that can identify when a bridge has developed vulnerabilities can provide important early warning systems so that infrastructure operators can prevent significant human and economic impacts of failures. Nature-based solutions, such as protecting wetlands or mangrove forests through appropriate planning of transportation infrastructure, can provide significant benefits with often minimal upfront investment and negligible ongoing operating costs.

Climate change is forcing aging water infrastructure to operate under extremes: either too little or too much

Water infrastructure in many regions is aging or underperforming.[28] In developed countries, most water infrastructure is aging rapidly. In the United States, roughly two-thirds of municipal city infrastructure is more than 30 years old, and in the United Kingdom, the average age of 800,000 kilometers of sewerage and water pipes is 70 years.[29] Segments of Europe's seven million kilometers of pipes are over 100 years old.[30] Although now rare in new construction, a legacy of combined sewage systems is common, carrying rainwater runoff, domestic sewage, and industrial wastewater. When rainwater surges, combined sewer overflows result.[31] In many cases, these systems are already straining under the load of societal growth, which reduces tolerance for climate hazards. In other parts of the world, two billion people still do not have basic sanitation facilities such as toilets or latrines.[32] Informal sanitation systems are more exposed to climate risks, and in the event of a disruption, they have a great risk of cross-contamination of waste and potable water.

26 Assessing the knock-on effects of flooding on road transportation: Katya Pyatkova et al., "Flood Impacts on Road Transportation Using Microscopic Traffic Modelling Techniques," in *Simulating Urban Traffic Scenarios: 3rd SUMO Conference 2015 Berlin, Germany,* Michael Behrisch and Melanie Weber, eds., Cham, Switzerland: Springer, 2019; Maria Pregnolato et al., "Impact of climate change on disruption to urban transport networks from pluvial flooding," Journal of Infrastructure Systems, December 2017, Volume 23, Number 4; Pablo Suarez et al., "Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area," *Transportation Research Part D: Transport and Environment,* May 2005, Volume 10, Number 3.

27 Richard Dawson et al., "Infrastructure," in *UK climate change risk assessment 2017 evidence report*, Committee on Climate Change, 2016.

28 Our analysis focuses on the ability of water infrastructure to perform in the context of a given climatic hazard, not the direct effects of water hazards on a population. For example, in a drought, our analysis considers how assets are prepared to maximize water availability and continue operation as long as possible.

29 Richard Dawson et al., "Infrastructure," in *UK climate change risk assessment 2017 evidence report*, Committee on Climate Change, 2016.

30 Klara Ramm, "Time to invest in Europe's water infrastructure," EURACTIV, May 2, 2018,

31 John Tibbetts, "Combined sewer systems: Down, dirty, and out of date," *Environmental Health Perspectives*, July 2005, Volume 113, Number 7.

32 World Health Organization, 2019.

Box 1.

How disruptive could extreme heat be to global air travel?

Extreme heat is already disrupting global air travel.[1] In July 2017, approximately 50 flights were grounded for physical and regulatory reasons when temperatures in Phoenix, Arizona, skyrocketed to 48 degrees Celsius.[2] As air temperature rises, the density of the air decreases and negatively affects lift. As a result, planes require a combination of more thrust, lighter takeoff weights, and longer runways to take off. Regulators build this into their decisions. Under US regulations, the Federal Aviation Administration and the International Air Transport Association certify aircraft to operate at temperatures below certain levels, depending on manufacturer and performance specifications and the elevation of the takeoff runway. Since extreme heat disruptions are expected to increase, we analyze the likely impact on passengers and air travel.

Operational thresholds vary based on International Standard Atmosphere conditions, which is partly a function of elevation and temperature. Many original equipment manufacturer thresholds are not publicly available, but they are typically lower for smaller, regional aircraft used most often on domestic flights. We have focused on these types of aircraft, for which 48 degrees is a rough threshold for conducting sensitivity analysis, based on available data.

Parts of the world can expect to see extreme high temperatures occur up to 21 days a year in 2030 and 36 days a year in 2050, which means heat groundings could become a far more common occurrence. The most affected regions will be the Persian Gulf, India, parts of Pakistan, and, to a lesser extent, parts of the southwestern United States, Central Asia, Australia, and the Sahara. We find that crucial hubs like Indira Gandhi International Airport in New Delhi, Dubai International Airport, Abu Dhabi International Airport, and Kuwait International Airport could be exposed to heat nearing or exceeding 50 degrees for at least six hours on two to seven days a year in 2030. This could reach up to 14 days a year by 2050. Other regions are also at risk. Several airports in the United States such as Kansas City, Little Rock, and Phoenix are projected to have a 5 percent chance every year of experiencing temperatures that approach 50 degrees by 2050.

Assuming regional aircraft are largely similar to today's and keeping the number of regional flights constant to isolate climate impact, if no adaptation measures are taken (for example, lengthening runways, improving aircraft technology), this translates into about 200 to 900 flights grounded per year by 2030 and about 500 to 2,200 flights by 2050 (Infrastructure-2). This could directly affect about 16,000 to 75,000 passengers per year in 2030 and about 40,000 to 185,000 passengers per year in 2050, up from an estimated 4,000 to 8,000 today (these events not systematically recorded today) from extreme heat. More or fewer passengers may be affected depending on whether heat waves strike on heavier travel days (when flights are fuller) and how long the heat conditions persist. Air transportation delays cost the US economy $4 billion in 2007, with most direct costs falling on passengers.[3]

However, well before temperatures reach anywhere close to 48 degrees, many aircraft of all sizes will have to decrease weight in order to take off, especially at higher elevations. One study has estimated the necessary reduction at about 4 percent of weight, on average across 19 evaluated airports for four common commercial airplane variants.[4] This study also found weight restrictions would increase most often in summer months (May to September), with a frequency of up to 80 percent by 2030 at several US airports (including Denver, La Guardia, Phoenix, and Reagan National), and by 50 to 200 percent as soon as 2050.[5] That would mean last-minute disruptions to passengers or cargo that cannot be brought on flight.

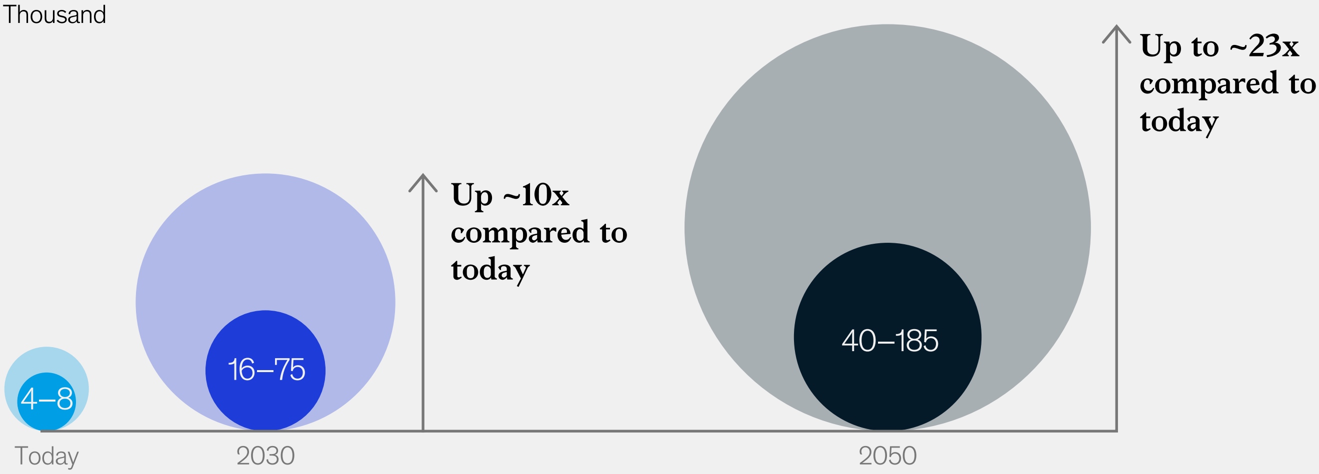
1 Our analysis excludes the impacts of the COVID-19 pandemic.
2 Rhett Allain, "Why Phoenix's airplanes can't take off in extreme heat," *Wired*, June 20, 2017.
3 Michael Ball et al., *Total delay impact study: A comprehensive assessment of the costs and impacts of flight delay in the United States*, National Center of Excellence for Aviation Operations Research (NEXTOR), October 2010.
4 Ethan D. Coffel, Terence R. Thompson, and Radley M. Horton, "The impacts of rising temperatures on aircraft takeoff performance," *Climatic Change*, September 2017, Volume 144, Number 2.
5 E. Coffel and R. Horton, "Climate change and the impact of extreme temperatures on aviation," *Weather, Climate, and Society*, January 2015, Volume 7, Number 1.

By 2050, up to 185,000 airline passengers per year may be grounded due to extreme heat (48°C), approximately 23 times more than today.

Based on RCP 8.5

Passengers affected by heat groundings each year[1]

Thousand



1. Assumes absence of targeted adaptation.

Assumptions: Covers aircraft typically used for regional flights; excludes larger international aircraft that have higher heat tolerances. Hazard is number of days when temperature reaches 48°C for at least 6 hours. Equal numbers of flights per day (no seasonal distribution applied). No growth in flights in future forecast. Heat-induced groundings are not widely documented today, but estimated at 50–100 per year based on a press search covering last 5 years, with allowance for underreporting. Based on RCP 8.5 scenario.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; Diio Mi flight database; Global Airport Database; Carpenter, 2018; McKinsey Global Institute analysis

Water supply systems

Water infrastructure is designed to deliver sufficient water within certain climate parameters, but these parameters have changed. In the case of water supply systems, the projected increasing frequency of droughts in many regions around the world will strain these systems. As a result of drought, water infrastructure will increasingly be unable to meet the needs of populations (See Box 2, "Chennai's 2019 water crisis and a possible response"). In many cases, supply redundancy built in at the design stage has already been lost as infrastructure degrades or as the user base grew beyond original design expectations, exacerbating shortfalls. In response, in the developed world, attempts to reduce the level of evaporation in reservoirs include the "shade balls" deployed in Los Angeles during the 2011–17 California drought. However, these require more water to make than they save, simply shifting the water burden rather than creating a net gain.[33] Consumption reduction programs such as hard limits or consumption pricing—whether for individual residents or for institutional consumers—can reduce demand but are often resisted and may have broader economic implications, particularly on water-intensive industries.

Water supply systems can also experience long-lasting outages from acute shocks like hurricanes and flooding. Two weeks after Hurricane Katrina in 2005, 70 percent of affected drinking water facilities were still offline.[34] Flooding can also result in long recovery periods. In 2007 the United Kingdom experienced widespread flooding, due to the wettest May-June period since records began in 1776; flooding of treatment plants cut off the supply of clean water in certain areas for 17 days.[35] The failure of large hydrological structures can represent a devastating threat to the surrounding area. In 2019, the partial collapse of a 200-year-old dam in Derbyshire in the United Kingdom put 1,400 lives at risk. Contamination of raw water and increased levels of sediment from storm runoff can increase water purification plants' costs.[36] Effects are more dramatic in the developing world, where contamination of drinking water is common, and cholera and E. coli frequently cause widespread diarrhea outbreaks in the aftermath of floods.[37] In response, alternate private water sources can be safer but typically cost ten to 100 times as much as existing systems. Household or hyper-local water treatment and purification systems can mitigate these costs but are unreliable and require sustained investment and attention both by users and providers. The travel involved for households in collecting water from remote sources has a number of societal knock-on effects, including exacerbating gender inequality.[38]

Wastewater systems

Wastewater systems also suffer as a result of drought, but to a lesser extent. Sewers can have inadequate flow, resulting in blockages and the inability to process human waste. Blockages lead to the possibility of sewage systems bursting in the middle of urban areas. During the 2018 Cape Town drought, wastewater processing in nine examined waste water plants fell by 17 to 52 percent.[39]

33 Erfan Haghighi, Kaveh Madani, and Arjen Y. Hoekstra, "The water footprint of water conservation using shade balls in California," *Nature Sustainability*, July 2018, Volume 1, Number 7.

34 Claudia Copeland, *Hurricane-damaged drinking water and wastewater facilities: Impacts, needs, and response*, Congressional Research Service, 2005.

35 Richard Dawson et al., "Infrastructure," in *UK climate change risk assessment 2017 evidence report*, Committee on Climate Change, 2016.

36 US Agency for International Development (USAID), *Addressing climate change impacts on infrastructure: Preparing for change*, November 2012, revised December 2013; Helen Pidd et al., "Peak District town evacuated as dam threatens to burst," *Guardian,* August 1, 2019, theguardian.com/uk-news/2019/aug/01/uk-weather-homes-evacuated-floods-hit-north-of-england.

37 Mike Ahern et al., "Global health impacts of floods: Epidemiological evidence," *Epidemiologic Reviews*, July 2005, Volume 27, Number 1; F. Qadri et al., "Enterotoxigenic Escherichia coli and Vibrio cholerae diarrhea, Bangladesh, 2004,“ *Emerging Infectious Diseases,* July 2005, Volume 11, Number 7.

38 United Nations Human Settlements Programme (UN-Habitat), 2003.

39 Jorisna Bonthuys, "Cape Town drought places sewerage systems under pressure," *Water Wheel*, May 2018, Volume 17, Number 3.

Box 2.

Chennai's 2019 water crisis and a possible response

In 2019, the chronic water stress afflicting Chennai, India, became an acute crisis. Three of the city's four main reservoirs dried up. Poor access to water distribution plagued the most impoverished residents.[1] The price of water doubled on the black market. Although drought was the principal driver of the crisis, better water infrastructure may have mitigated its impact. For example, storage infrastructure could have been upgraded to make better use of water during flood periods. Chennai was inundated by strong rains in 2015, but the city's four main storage facilities at full capacity hold less than a year's water demand.[2] Improving maintenance could also stem water losses.[3] More micro efforts, such as rainwater harvesting, are underexploited in the region and could reduce strain. Connections between supply sources and permanent infrastructure could be improved; in 2019, water had to be moved by trains and tankers more than 216 kilometers. A lack of formal supply results in significant unregulated access, both limiting the ability to manage demand during droughts and increasing the likelihood of drought over time.[4]

1 Karen Coelho, "Chennai drought: How water distribution system reflects residents' social power, bias against poor," Scroll.in, July 23, 2019; Raj Bhagat Palanichamy, "Lifting Chennai out of drought," *The Hindu*, June 30, 2019.

2 "Summer of despair for parched Chennai: Authorities struggle to meet water demand," *Times of India*, May 9, 2019; "Tamil Nadu water woes: Chennai goes thirsty, business feels the heat," *Business Standard,* June 17, 2019; Veena Srinivasan, "Wake up, there's no water!," *Deccan Herald*, June 23, 2019.

3 "The Water crisis in Chennai, India: Who's to blame and how do you fix it?," NPR, July 18, 2019.

4 Informal groundwater extraction has caused Bangalore's water table to plunge to depths of nearly 1,000 feet. Arati Kumar-Rao, "India's water crisis could be helped by better building, planning," *National Geographic*, July 15, 2019; "Parched manufacturing city in India brings in water by rail," Associated Press, July 29, 2019.

The biggest threat to wastewater systems is flooding. During Hurricane Sandy, extreme precipitation and storm surge combined to overwhelm wastewater systems, leading to the release of more than ten billion gallons of untreated and partially treated sewage into estuaries, bays, and coastlines in New York and New Jersey.[40] Sewage impacts have been associated with diseases and significant damage to local wildlife.[41] Similar but more gradual wastewater overflows are also happening because of chronic stresses. In 2018, rainfall in the city of Richmond, Virginia, was more than 50 percent above average, and as a result 15,500 cubic meters of untreated sewage spilled into the James River. The Environmental Protection Agency estimated that in 2004, 1.8 million to 3.5 million Americans had infectious waterborne illnesses associated with swimming in sewage-contaminated coastal waters. This is likely an underestimate due to underreporting. Whatever the true value, it is expected to increase with rising storm runoff.[42] Adaptation responses include investments in separating sewage from stormwater systems, extending lines, and expanding overall system capacity. Other nature-based solutions may be effective in some of these cases, including expanding permeable surfaces (for example, parks) in cities to absorb water into the ground instead of directing it to stormwater systems, and using natural features such as creek and river systems to disperse excess water in multiple directions.

40 Ben Bovarnick, Shiva Polefka, and Arpita Bhattacharyya, *Rising waters, rising threat*, Center for American Progress, October 31, 2014; Alyson Kenward, Daniel Yawitz, and Urooj Raja, *Sewage overflows from Hurricane Sandy*, Climate Central, 2013.

41 "SSO fact sheet: Why control sanitary sewer overflows?," US Environmental Protection Agency, 2003.

42 Ibid.

Telecommunications is a fast-growing sector, giving its infrastructure more agility and redundancy, yet as the world's dependence on the communications network increases, climate risks will also grow

Much of the global economy increasingly depends on telecommunications infrastructure. The world's reliance on digital connectivity has risen exponentially, increasing vulnerability to climate disruptions. In 1995, less than 1 percent of the world's population was online; by 2019, more than half had access.[43] Public safety networks rely on functional information and communications technology (ICT) infrastructure, particularly wireless. In the United States, for example, 70 percent of emergency phone calls are made from a mobile device.[44]

ICT is projected to fuel further economic expansion of up to 10 percent of GDP in Europe by 2025.[45] As economies digitize, the resilience of physical infrastructure becomes increasingly important. The average cost of data center outages has risen significantly over the past five years and is now estimated at about $9,000 per minute.[46] The knock-on effects of failures are global. Brief data center failures in the past three years have grounded 75,000 vacationers in the United Kingdom, taken down major news websites in the United States, and prevented access to banking systems for hours.[47]

The risks climate change presents for telecom are primarily acute. High winds or trees can fell cell phone towers and telephone poles, blow down telephone lines and base stations, and knock microwave receivers out of alignment. Above-ground cabling is at more risk than buried lines of support and pole failures, damage from debris and falling objects (such as trees), and breakage from tension caused by extreme wind speeds.[48] Flooding and hurricanes are the biggest threats. In 2015–16, floods in the United Kingdom inundated a number of key telecom assets, cutting off thousands of homes, businesses (which lost access to ATMs and other systems), and critical public services such as the police.[49] Hurricanes Irma and Maria caused devastation to telecom infrastructure in the Caribbean, with over 90 percent of mobile sites destroyed in Puerto Rico, St. Martin, Dominica, and Antigua and Barbuda.[50] These threats interfere with the system just when it is needed most for disaster recovery. Communication blackouts can hamper disaster relief and the management of infrastructure repair efforts. Even systems that survive hazards can become congested and fail, as occurred in Thailand after the 2004 Indian Ocean tsunami. In addition, unreliable communications infrastructure costs lives through poorly performing early-warning systems.[51]

Chronic impacts also exist, but this risk is typically lower. Higher heat can increase data centers' cooling costs, which make up 40 percent of their total energy consumed.[52] Rain can affect mobile signals ("rain shading"), but this is predominantly a problem above 10 gigahertz and so is rare.

Interdependencies particularly exacerbate telecom's climate risk. The sector is increasingly dependent on electricity and is vulnerable to blackouts. Most cell phone towers only have up to eight hours of backup power.[53] Water, too, is needed for cooling; Google, Microsoft, and Apple have all invested in their own water treatment plants to ensure supply. Many of

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43 International Telecommunication Union (ITU), 2019; Internet World Stats.
44 Bay/North Coast Broadband Consortium, *Telecommunications outage report: Northern California firestorm 2017*, April 2018.
45 *Digital Europe: Pushing the frontier, capturing the benefits*, McKinsey Global Institute, 2016; Rudra P. Pradhan, Girijasankar Mallik, and Tapan P. Bagchi, "Information communication technology (ICT) infrastructure and economic growth: A causality evinced by cross-country panel data," *IIMB Management Review*, March 2018, Volume 30, Number 1.
46 Eaton, *Blackout tracker: United States annual report 2015*, 2016.
47 Yevgeniy Sverdlik, "CBRE settles British Airways lawsuit over costly data center outage," Data Center Knowledge, Feb 12, 2019.
48 USAID, *Addressing climate change impacts on infrastructure: Preparing for change*, November 2012, revised December 2013.
49 Richard Dawson et al., "Infrastructure," in *UK climate change risk assessment 2017 evidence report*, Committee on Climate Change, 2016.
50 GSMA, *The 2017 Atlantic hurricane season: Mobile industry impact and response in the Caribbean*, March 2018.
51 Anthony M. Townsend and Mitchell L. Moss, *Telecommunications infrastructure in disasters: Preparing cities for crisis communications,* New York University, April 2005.
52 Z. Song, Xiaojing Zhang, and Clas Eriksson, "Data center energy and cost saving evaluation," *Energy Procedia,* August 2015, Volume 75.
53 US Federal Energy Regulatory Commission, *Long-term, large-scale blackout scenario*, 2017.

the adaptation and mitigation measures proposed for climate change also rely on the use of digital technology, such as increased working from home—which currently applies to 4.5 million people in the United Kingdom alone—to smart energy grids (including storage) to advanced analytics for transportation systems.[54]

On the other hand, the telecom sector has some unique characteristics that may mitigate risks over time and support rapid adaptation. The average asset has a shorter design life than those in other infrastructure sectors (roughly 25 years for a data center, for example), and the equipment on or within assets likely has an even shorter design life (and may change every two to five years), allowing for the introduction of more resilient assets earlier.[55] The telecom industry is likely to be able to introduce redundancy faster than more physical systems like power and water due to high levels of competition in some areas (such as GSM coverage).[56] This provides an opportunity to adapt to climate risks by expanding the ranges of climate hazards that such systems can be exposed to. At the same time, redundancies are also complex and tend to grow organically. Not all interdependencies are fully understood, and rapid advancements may suddenly present unexpected vulnerabilities.[57] Many specialized pieces of telecom equipment are also more exposed to supply chain risk compared with the concrete involved in the creation of a dam, for example.[58]

The real threat to telecom may be uncertainty. Compared with the other sectors examined, the full scale of the impact and how failures may play out are much less clear. Many assets are young, additional complexities are being built into systems, and more critical systems are becoming digitized. This creates a potential scenario in which consequences are both severe and hard to predict. As a result, the impact of climate change may also be hard to prevent.[59]

Adapting infrastructure to rising climate risks will require greater transparency, changes to design, and significantly greater funding

How global infrastructure evolves over the next 50 years may be a major determinant of the impact of climate change on civilization. More money will need to be spent both on and in support of infrastructure, and in new ways. Building slightly higher walls, metaphorically or literally, may not be the best solution. And the risks extend beyond infrastructure. A failure to adapt by not taking climate change into account in the design, construction, and maintenance of infrastructure assets will not only cause costs to owners and operators but will leave entire communities exposed and vulnerable. Adaptation can deliver a strong return both by reducing costs from climate-related damage to infrastructure itself and by avoiding significant knock-on effects in wider society.

Infrastructure is expected to bear the brunt of expected climate change adaptation costs, typically estimated to be between 60 and 80 percent of total climate change adaptation spending globally, which could average $150 billion to $450 billion per year on infrastructure in 2050.[60] However, most estimates of the cost of adaptation relative to current assets are small compared with the scale of infrastructure investments. Estimates vary significantly, but consensus puts adaptation spending for new assets at about 1 to 2 percent of total infrastructure spending a year.[61] Still, this may hide significant variation in the type of asset.

54 "Homeworkers by UK region, 2008 compared with 2018," ONS, 2018.
55 UK Department for Environment, Food & Rural Affairs, *Adapting the ICT sector to the impacts of climate change*, 2010.
56 Ibid.
57 Tech UK, *The UK's core digital infrastructure: Data centres climate change adaptation and resilience*, December 2016.
58 Peter Adams et al., *Climate risks study for telecommunications and data center services: Report prepared for the General Services Administration*, Riverside Technology and Acclimatise, 2014.
59 UK Department for Environment, Food & Rural Affairs, *Adapting the ICT sector to the impacts of climate change*, 2010.
60 *Economics of Adaptation to Climate Change*, World Bank, 2010; United Nations Environment Programme, *The adaptation gap report 2018*, 2018; United Nations Framework Convention on Climate Change (UNFCCC); *Assessing the costs of adaptation to climate change: A review of the UNFCCC and other recent estimates,* International Institute for Environment and Development and Grantham Institute for Climate Change, August 2009. Uses proportions of adaptation costs related to infrastructure adaptation, flood defenses, and water supply spending from earlier, more granular reports and applies them to the latest total forecasts.
61 Gordon Hughes, Paul Chinowsky, and Ken Strzepek, *The costs of adapting to climate change for infrastructure*, World Bank, 2007.

Depending on technical factors, location, age, downtime requirements, and other factors, some assets will be significantly more costly to adapt than others.

While infrastructure adaptation pays, not all adaptation will pay equally. A positive spectrum of returns exists, dependent on the type of intervention and the nature of hazard addressed. If we divide, for example, the lifetime cost-avoidance over the cost of an adaptation investment in some assets, the best-performing infrastructure investments may present a return of five to ten times.[62] Those with the greatest financial returns will be those that are the most strategic (such as adjusting future infrastructure locations and standards rather than hardening assets once in place), those that protect the highest density of assets (although there are critical equity, social, and human reasons for protecting communities that may not meet these criteria), and those that have other positive spillover effects (for example, grid efficiency improvements that provide more redundancy and lower cost).

Capturing the value from adaptation investment will require meaningful sharing of risk and reward; this may require a step change in private-private and public-private collaboration. Since many of the benefits are public goods, private operators will need to find models that share benefits and costs. Considering the density of infrastructure systems, owners may find co-investing a means to gain economies of scale. Conversely, inaction by one stakeholder can severely undermine the action of others (in the most literal terms, for example, a gap in a floodwall). When considering participation in these relationships, parties will need to think of broader definitions of value and more probabilistic approaches to sizing it; this will be true not only for societal knock-on effects, but also for commercial factors such as reputational damage. When needs are concentrated in developing parts of the world, more complex collaborations may be required between stakeholders, possibly transcending national boundaries.

Adaptation should be tailored to the specific hazard and infrastructure risks. However, opportunities exist for adaptation that are relevant for all infrastructure sectors. Examples of ways to adapt current and future infrastructure to climate risks can be considered:

Reduce exposure through transparency

— Specify situating assets on the basis of climate-aware risk; reduce incentives for infrastructure builders and operators to function in high-risk areas; discourage impact exacerbating developments (such as large non-porous areas).

— Create land use policies and practices that minimize construction in vulnerable areas, and leverage natural assets such as wetlands and mangroves

— Increase overall transparency of risk, including in public reporting, asset evaluations, investment decisions, etc.

— Develop early-warning systems, evacuation protocols, citizen engagement, and preparation education

— Include climate change in all business case evaluations for infrastructure (for example, portfolio risk assessments, asset underwriting)

Accelerate investment in resilience

— Decentralize energy grids (for example, use of energy storage); increase efficiencies in power, transportation, and telecom to provide headroom and enhance the versatility of public assets (for instance, road tunnels that can be converted to storm surge drainage).

[62] Global Commission on Adaptation, *Adapt Now: A Global Call for Leadership on Climate Resilience*, 2019

— Apply existing best practice construction techniques, such as adaptation techniques that are already functional (for example, increase tower height, bury distribution lines, move facilities further away from hazards)

— Invest in resilient infrastructure that has multiple benefits (for example, a public park that can be used to contain and direct flooding)

— Construct assets that maximize energy, water, and other forms of efficiency (for example, passive buildings that can operate during grid level blackouts)

— Deploy new, resilient technologies to improve the resilience of infrastructure (for example, smart grids, embedded sensor layers)

— Critically review design standards and codes to ensure it takes into account current and coming risk levels

— Use modular infrastructure design to enable rapid replacement of damaged components (for example,modular energy infrastructure)

— Incorporate resilience into procurement standards (for example, ensure lifetime performance under expected climate conditions)

Mobilize capital to fund adaptation

— Create operational models that allow infrastructure operators to raise funds for adaptation measures; transfer remaining risk to third parties including government after all other cost-effective measures have been implemented.

— Create mechanisms to capture land value appreciation from adaptation investment to fund adaptation measures (for example, similar to tax increment financing)

— Develop local infrastructure funds that target shared, local adaptation measures (for example, similar to business improvement district investments)

— Expand the duration of government funding periods for regulated entities to enable adaptation investments that take into account longer time horizons (for example, extending grant cycles for water utilities)

— Divest assets that are exposed to—or contribute to—climate risks and use proceeds to invest in adaptation infrastructure (for example, Australia’s program of recycling funds from the sale of some infrastructure assets into the construction of new infrastructure assets with greater public benefits)

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